THE DEEP OCEAN CRITICAL HEAT TRANSFER (DOOM) PROGRAM

By

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18 JANUARY 1971

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THE DEEP OCEAN OPTICAL MEASUREMENT (DOOM) PROGRAM

Prepared by:
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ABSTRACT: A ship borne system is described and results of
in-situ measurements of the inherent optical properties of
ocean water are presented. This Deep Ocean Optical Measurement
(DOOM) system is designed to measure to any depth in the ocean
spectral attenuation coefficients from 380 to 560 millimicrons,
the volume scattering function at 436 millimicrons through an
angular range from six to 92 degrees, and background illumination
of both celestrial and biological origin. Representative data
obtained from December 1967 through January 1970 on six
measurement cruises to various areas of the Atlantic are
presented. Future cruises and plans are discussed.

NAVAL ORDNANCE LABORATORY
WHITE OAK, MARYLAND

NOLTR 70-165   18 January 1971

The Deep Ocean Optical Measurement (DOOM) Program

The measurement program described in this report was conducted
by the Optical Oceanography Section of the Radiation Physics
Division (formerly the Infrared Group of the Solid State
Division) of the Applied Physics Department. The work was
performed for the Naval Ordnance Systems Command's ASW
Oceanographic Research Program under Task Number
ORD-03C-000/092-1/R104-03-01. This report is for information
only and is not intended as a recommendation for action.

Grateful acknowledgement is extended to the following colleagues
at NOL who have significantly contributed to the DOOM program:
H. A. Templin, G. M. Black, R. W. Rogers, J. R. Lowney,
W. W. Talbert, W. Proffit and J. Lamberth.

The author also wishes to thank the personnel of the Operations
Office and the Atlantic Coordination Section, Research Ship
Branch of the U. S. Naval Oceanographic Office for their
support in scheduling and coordinating the measurement cruises.
Appreciation is also extended to the officers and crew of the
research ships, the USNS GILLISS and LYNCH.

                         GEORGE G. BALL
                         Captain, USN
                         Commander

                         W. W. Scanlon

                         W. W. SCANLON
                         By direction

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Chapter 1

INTRODUCTION

Of the mar / physical problems confronting man's exploration of the sea, perhaps the most confining is the degradation of vision when venturing beneath the surface of the world's oceans. In the atmosphere man with his optical instruments may view past the horizon or probe into the far reaches of space, but on entry into the hydrosphere, even with the most sophisticated of optical instruments his visibility is limited to but tens of feet. At depths below several hundred meters the ocean becomes a realm of perpetual darkness, where sources of artificial illumination are a requisite even for marginal viewing. Although sonar systems, because of low attenuation losses in water, have been employed extensively and quite successfully in a large number of undersea applications, their performance is not to be confused with that of quality optical devices - in terms of information rate and imaging quality. The inherent nature of sound propagation in water limits the information rate and resolution of sonic devices by several orders of magnitude as compared to optical systems. Optical wavelengths unfortunately suffer severe transmission losses in aqueous media; thus very bright source lights at these wavelengths are required even for modest viewing ranges.

The recent development of the laser which holds promise of being an unexcelled source for underwater applications has stimulated interest in light propagation through water and led to a number of studies at NOL and elsewhere (a, b, c). Laboratory measurements of the spectral attenuation coefficients at several wavelengths for tap, distilled, and filtered water were made at NOL during the mid sixties. Propagation of pulsed green laser light (530 m_μ) in water was investigated during field tests (a) in a 2500-foot model basin at the Naval Ship Research and Development Center, Carderock, Maryland. Further studies of lasers in water were conducted with both the pulsed green laser and a continuous wave gas laser operated in the red (632.8 m_μ) in the 100-foot vertical undersea weapons tank at NOL (d). The above studies confirmed the belief that coherent laser emissions are attenuated and scattered in the same manner and by the same mechanisms as conventional incoherent light sources. Thus measurements with conventional optical instruments may be validly applied to studies of laser systems for underwater naval use.

A Deep Ocean Optical Measurement (DOOM) program was initiated at NOL in 1966 for the purpose of measuring in-situ the optical properties of the ocean which influence underwater light transmissions. Although many studies of absorption and scattering by natural waters have been made, (e, -k) these have lacked the cohesiveness which would provide an adequate picture of the attenuation phenomena in the sea. Some shortcomings of past studies are the following:

(1) Measurements were not made in-situ but with collected water samples either in the laboratory or aboard ship, thus disturbing the biological and dynamic physical processes occurring in the ocean.

(2) Only one optical parameter was measured either attenuation or scattering, without correlating the two.

(3) Information from the depths of the ocean basins is quite meager.

(4) Equipments were old and unsophisticated resulting in data of questionable accuracy. The objective of the DOOM program is to measure quantitatively under controlled optical conditions with modern instrumentation the optical properties at all depths of Atlantic and Caribbean ocean waters.

This report will describe in detail the instrumentation and techniques developed to fulfill this objective. Sea trials to date will be discussed briefly and examples of typical data will be presented.

Chapter 2

THEORY

Optical properties of the ocean may be divided into
two separate classes, the inherent properties and the apparent
properties[1] The former are intrinsic physical properties of
the medium and determine the manner in which a beam of light
is propagated within that medium. They are independent of the
orientation of the beam and of the existing light fields within
the medium. Apparent optical properties depend in a rather
complicated way on the inherent properties and are dependent
on the geometric structure of the various light fields in
the medium. Inherent properties measured by DOOM are the
attenuation coefficient and the volume scattering function.

If a collimated beam of light is propagated through water
over a path of length x, the radiant power of P_x remaining is
given by

$$P_x = P_o e^{-\alpha x}$$

where P_o represents the total flux initially in the beam. The
total attenuation coefficient α, defined by this equation,
has the dimensions of reciprocal length and in this report
will be expressed in units of reciprocal meters (m^{-1}). In
theory P_x excludes flux that has been deviated by any scattering
process, but in practice all functional measuring devices do
accept both single and multiple scattered flux from small
forward angles that are within the receiver field of view.

Attenuation coefficients of electromagnetic radiation in
all waters, both pure and natural, are a marked function of
wavelength; the only real window in the entire spectrum falls
in the visible near 480 mμ. Spectral attenuation coefficients
of pure water prepared and measured in the laboratory by several
investigators are presented in Figure 1. The pure water of
Matlack was prepared by filtering demineralized tap water
through 0.22 μ pore size millipore seives, while multiple
distillation was employed in the preparation of the other
samples. In addition to the NOL measurement are the much
referenced works of Hulbert (h) and a more recent effort by
Sullivan (m) which exhibits a somewhat higher transmission in
the blue-violet. The work of Sawyer (e) from the 1930's is
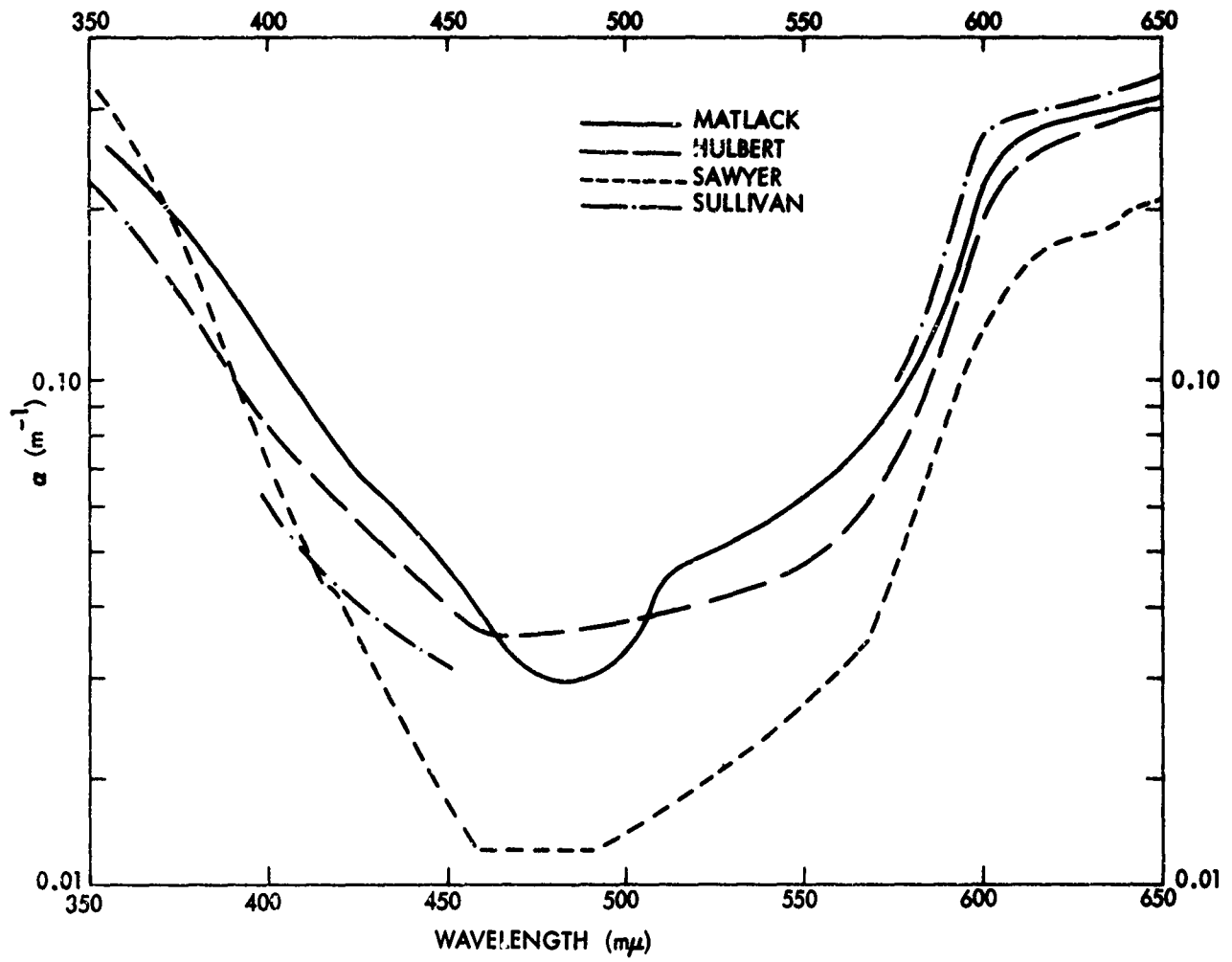typical of some of the earlier results which yielded lower

FIG. 1 OPTICAL ATTENUATION SPECTRA OF PURE WATER SAMPLES

coefficients and consequently higher water transmissions than are believed correct today. The curves of the other observers which in general agree in magnitude, shape, and location of the window, represent currently accepted levels of minimum attenuation in water.

Attenuation of light in water results from two independent mechanisms: absorption and scattering. Absorption includes all processes where radiant flux is converted into other forms of energy, such as the irreversible thermodynamic conversion to kinetic energy. Scattering is a random process by which individual photons are deviated and thus lost from the original beam of light. The attenuation coefficient α is the sum of the absorption coefficient a and the total volume scattering coefficient s, thus

$$\alpha = a + s.$$

To determine that portion of the attenuation due to scattering, consider an elemental volume dv within a collimated beam of monochromatic light as in Figure 2. Let H be the irradiance input to dv and $dJ(\theta)$ be the radiant intensity of light scattered in the direction θ. The volume scattering function $\sigma(\theta)$ is defined by the equation:

$$\sigma(\theta) = dJ(\theta)/Hdv$$

so $\sigma(\theta)$ is a measure of the light from the beam that is scattered per unit volume of water per unit solid angle in the direction θ. Its unit is commonly expressed in steradian $^{-1}$ meter $^{-1}$. If σ is integrated over the entire solid angle (Ω) about dv, the total volume scattering coefficient s is obtained; thus

$$s = \oint \sigma d\Omega = 2\pi \int_0^\pi \sigma \sin \theta \, d\theta$$

where it has been assumed that the scattering is symmetrical about the beam. Its unit is expressed in reciprocal meters (m^{-1}).

Scattering in pure water must be considered on a molecular level and may be described by the Raleigh equation (n) or by the Smoluchowski Einstein fluctuation theory (o, p). Spectral distribution will vary as the inverse fourth power of the wdvelength and the angular distribution as $(1 + 0.835 \cos^2\theta)$ (j). In practice however it is virtually impossible to obtain water completely free of particulate matter, so in all probability perfectly clean water has never been measured. The theoretical volume scattering function and those measured from pure water samples in the laboratory are presented in Figure 3. (h, q) Although the functions have been measured at different wavelengths, the shape of the curves show the departure from the theoretical thus indicating the presence of foreign particulate matter.
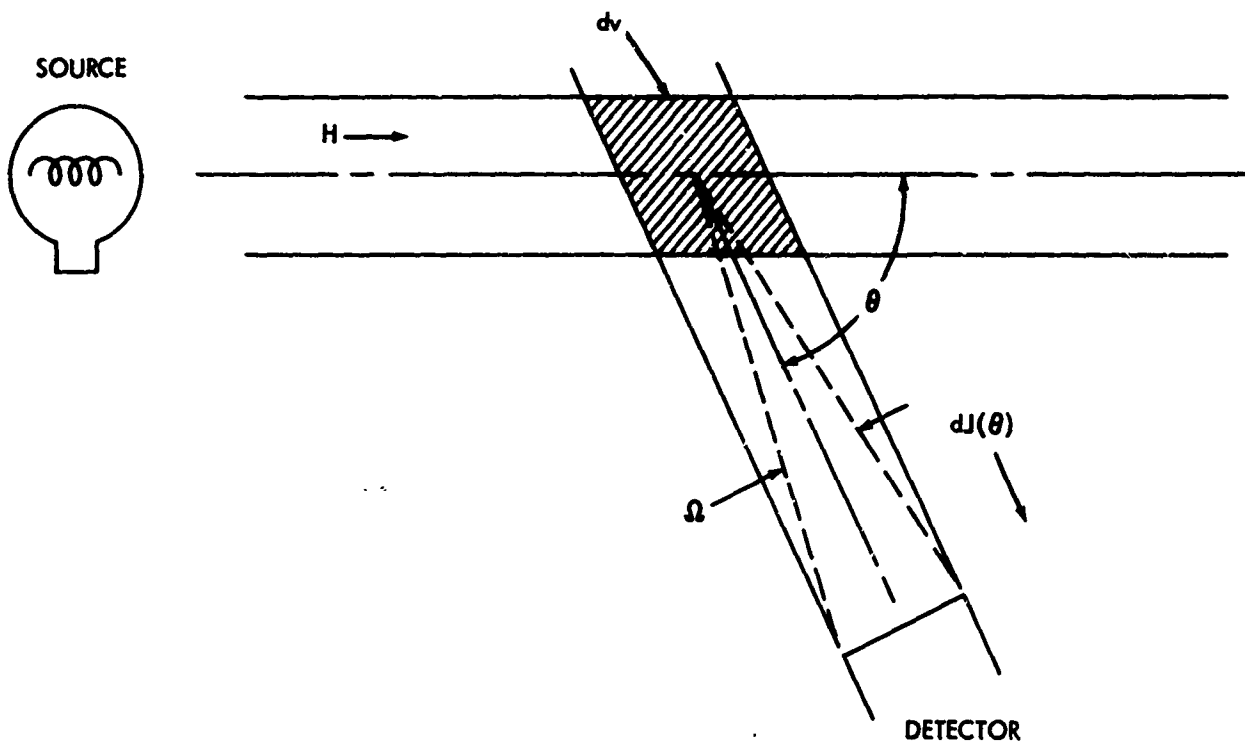
FIG. 2 SCHEMATIC DRAWING FOR DERIVING THE VOLUME SCATTERING FUNCTION $\sigma(\theta)$
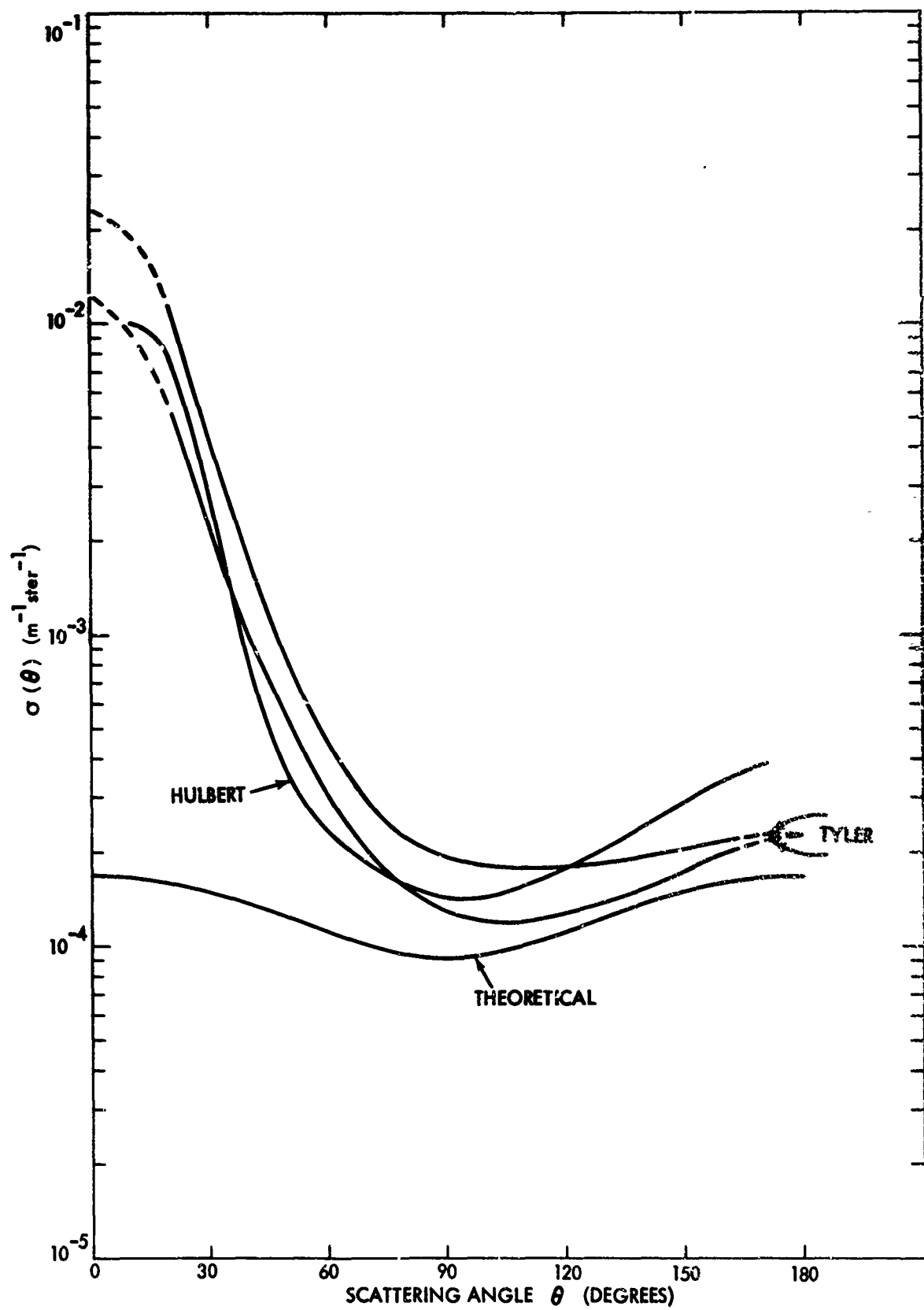
FIG.3 VOLUME SCATTERING FUNCTION OF DISTILLED WATER SAMPLES AS MEASURED BY HULBERT
FOR TUNGSTEN LIGHT AND TYLER AT 522 in μ

Since two independent mechanisms, scattering and absorption, govern water clarity, no single quantity can adequately specify the attenuance of light in natural water. Rather a combination is required such as the attenuation coefficient α and the total volume scattering coefficient s. A compilation for pure water of spectral α after Hulbert (h) and spectral s for the theoretical case from Le Grand (r) is presented in Table I. From the magnitude of the coefficients, it is evident that the spectral attenuation is much more strongly dependent upon selective absorption than the inverse fourth power wavelength scattering term.

The nature of the attenuation processes become much more complicated when natural waters are considered due to the presence of dissolved and suspended impurities within the media. Spectral attenuation of natural waters vary over wide ranges as indicated by the measurements of Figure 4 (h). Factors which may influence the transmission of light in sea water are (1) dissolved inorganic salts, (2) yellow substance, and (3) suspended particulate matter, both inorganic and organic. Studies by several observers (f, m) have substantially proved that dissolved salts in the sea exert virtually no influence on light transmission. Yellow substances are dissolved organic compounds, consisting of humic acid, melanoidins, and other compounds which result from the decomposition of plant and animal life. Attenuation by yellow substance, which is prominent in coastal and surface waters, increases towards the shorter wavelengths and when strong results in a shift of the transmission window at 480 m_μ towards the longer wavelengths. (s). Inorganic particulate matter consists of opaque and transparent mineral particles such as silt which in general have diameters large relative to the wavelength of visible light. Organic particulate material includes the plankton populations, both zoo- and phyto-, of the surface layers and the associated detritus produced by the biological kingdom within the sea. Planktonic organisms, many of which are transparent and range in size from microns to centimeters, both scatter and absorb light thus increasing attenuation. Selective absorption by these organisms tends to increase attenuation towards the shorter wavelengths. Since the size of suspended particulate materials in natural waters is usually large compared to the wavelength of light, spectral scattering no longer follows the Einstein relationship as in the pure water case, but becomes essentially independent of wavelength.

Background radiant flux within the ocean may originate from two basic areas, (1) the atmosphere and celestrial bodies in space and (2) from the luminescent organisms contained within the hydrospace itself. Illumination entering the ocean's surface from above is basically derived from the sun with some contributions from the sky, moon, and stars. The level of illumination at the surface, which varies both seasonally and diurnally, may change by as much as nine orders on magnitude during transition from full sunlight to the overcast night sky.

TABLE I

Measured Spectral Attenuation Coefficients
and Theoretical Scattering Coefficients for
Pure Water

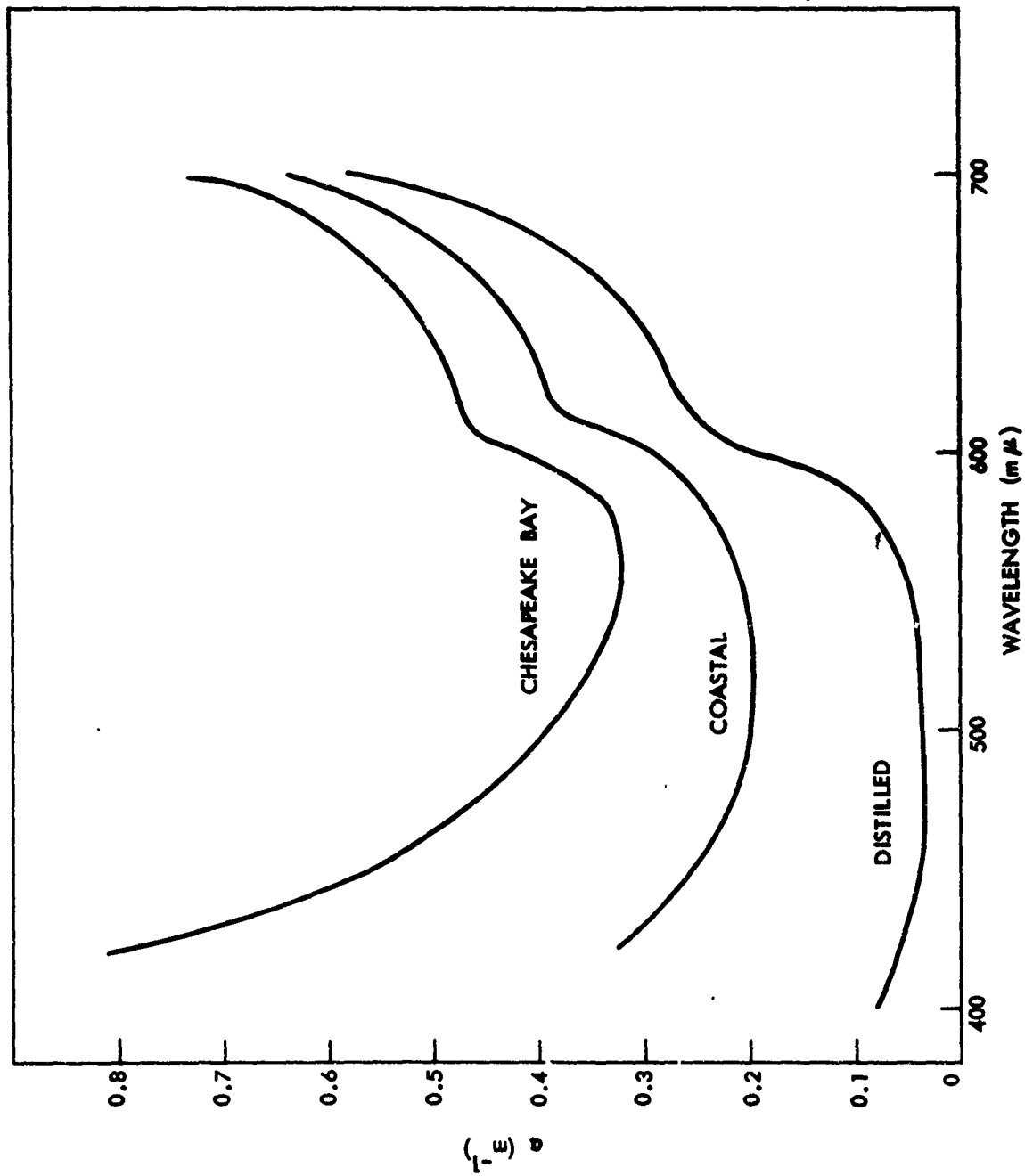| $\lambda(m\mu)$	$\alpha(10^3 m^{-1})$	$s(10^3 m^{-1})$
400	80	5.03
425	57	3.89
450	40	3.05
475	36	2.43
500	38	1.97
525	41	1.60
550	47	1.33
575	75	1.11
600	197	0.93
625	273	0.78
650	308	0.67
675	390	0.58
700	576	0.49

FIG.4 SPECTRAL ATTENUATION OF DISTILLED AND NATURAL WATERS FROM HULBERT

Radiant flux entering the ocean is attenuated exponentially with depth as e^{-Kd} where K is the diffuse vertical attenuation coefficient and d is the ocean depth. The euphotic zone is the region where ample light is available for photosynthesis. Depending on water clarity, it extends to depths of from 60 to 150 meters. Below this zone the remaining light is blue-green due to selective attenuation and K approaches a nearly constant value. Although lower values have been recorded, the diffuse coefficient K nominally ranges from 0.03 to 0.04 m^{-1} for clear ocean waters and from 0.05 to 0.15 m^{-1} for surface and coastal waters.[s] Surface illumination in clear ocean waters has been detected by photoelectric devices at depths in excess of 800 meters.

Precise measurement of K at these depths is complicated by the presence of luminescence from marine organisms which may contribute at low light levels a significant portion of the total flux present. Bioluminescence, either spontaneous or stimulated, generally occurs as flashes of light ranging in duration from less than 0.2 seconds to more than one second. In all ocean areas thus far investigated by a number of observers (t, u), some bioluminescent flashing was recorded at every depth where it could be distinguished above ambient background illumination. The frequency of flashing reported varied from a maximum of 160 per minute in certain surface layers to one per minute at a depth of 3750 meters. Spectral emissions, peaked in the blue-green transmission window, have produced peak irradiances greater than 10^{-2} microwatts per cm^2. [s]

Although a great many kinds of marine organisms are known to emit luminescent light, it appears that most flashing is produced by small organisms ranging in size from one centimeter to the microscopic unicellular forms. Continuous physical agitation of ocean water off Puerto Rico containing large populations of the tiny dinoflagellates stimulated a sustained irradiance of about 10^{-2} microwatts/cm^2. (v) Optical stimulation, in the form of a pulse train from a Xenon arc lamp have similarly produced in-situ sustained luminescence that exceeds the background radiance by as much as a factor of 10^4. (x)

Chapter 3

INSTRUMENTATION

The Deep Ocean Optical Measurement (DOOM) system is a self-contained, internally powered research instrument designed to measure simultaneously to any depth in the ocean the spectral attenuation coefficient, total volume scattering coefficient, and levels of background illumination. As pictured in Figure 5, the DOOM system continuously samples and records optical data as it is lowered on a wire rope from the mother ship to the ocean bottom. The metal framework, which serves to support the system on deck as well as protecting it from impact during handling, contains the following basic components:

(1) Instrument sphere
(2) Optics cylinder
(3) Pressure temperature probe
(4) Abyssal pinger
(5) External White mirror system
(6) Stepping motor

This framework is eight feet in length, three feet wide, and the top of the sphere stands about four feet off the deck. Total weight in air is about 2200 pounds, in water some 600 pounds lighter. Both the instrument sphere and optics cylinder are watertight housings fabricated of inch-thick precipitated hardened stainless steel designed to withstand hydrostatic pressure to 20,000 psi. The sphere has an inside diameter of 29 inches, the cylinder an ID of 12 inches and a total length of 32 inches. Equipment within the sphere supplies the measurement system with necessary power, control, signal processing, and signal recording functions. Electrical continuity between the sphere and cylinder is provided by multi-conductor connector and cable assembly proof tested to 20,000 psi. The optics cylinder houses separate optical instruments for the measurement of attenuation, scattering and background. Light enters and emerges from the cylinder through a total of five windows of one inch thick fused quartz each of which provides a free aperture of 20.6 mm. An eight pass White mirror system provides a 7.5 meter folded external light path in water for the attenuation measurement section. Light emerging from the scattering section is deflected through varying angular increments by a mirror attached to a deep sea stepping motor thus providing a measurement of the scattering function $\sigma(\theta)$. Pressure and

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DEEP OCEAN OPTICAL
MEASUREMENT SYSTEM
IN – SITU

FIG. 5 ARTIST'S RENDITION OF DOOM

temperature are continually recorded to all depths by the
external PT probe. Signals from the abyssal pinger are used
to determine the distance of the package from the bottom.

The spectral attenuation measurement section is shown
schematically in Figure 6. Light from a coiled filament
tungsten lamp is imaged on the entrance slit of a Littrow type
reflectance grating monochrometer. Spectral slit width
of the monochromatic as determined by the 600 groove/mm grating,
the 125 mm focal length collimating lens L2, and the 0.5 mm slit
widths, is essentially constant at 6.6 m_μ over the useful
spectral range of the instrument. Wavelength scanning is
accomplished by rotating the grating with an eighteen step
cam driven by an AC synchronous motor at rates of either
one or two RPM. A spectral interval of about 170 m_μ, scanned
in 10 m_μ incremental steps, is positioned in the near UV
and visible wavelength regions. The exit slit of the monochrometer
is imaged by the field lens L3 through the quartz window A
into the water at the entrance plane I1 (Figure 7) of the White
system. The field stop A1, also imaged by L3 but at the primary
mirror M1 of the White system, restricts the light bundle diameter
to 44 mm in air and 33 mm in water. Positions of these images
are the same in air as in water because the quartz windows have
been fabricated with a slight negative curvature. An eight pass
White optical system, attached on the outside of the cylinder
provides a 7.5 meter external water path. Three 76 mm diameter
mirrors with radii of curvature 910 mm, aluminized on the front
surface and overcoated with silicon monoxide for salt water
protection, fold the light for eight water passes in the manner
shown in Figure 7. Light leaving the White system enters the
cylinder through window B, is collected by lens L4 and eventually
imaged on the cathode of the photosensor, an S4 spectral response
photomultiplier tube. Appropriate field and aperture stops limit
the field of view of the sensor so it accepts only light reflected
within the solid angle subtended by the third mirror M3 of the
White system. The function of the Wratten filter Number CC50M
is to modify the spectral content of flux received from the
tungsten lamp so that the output signal of the S4 photomultiplier
is more uniform with wavelength. Chopping of the light at the
exit slit of the monochrometer permits the receiver electronics
to differentiate between the DC background light and that of
the chopped AC source and also facilitates signal processing.
In order to provide a reference signal in case of changes in
system responsivity, a portion of the source energy is deflected
by a beam splitter directly to the sensor optics. Mirrored and
open segments of a reference wheel are positioned in the reference
and α signal beams by a stepper motor synchronized with the
grating drive. During the normal α measurement, light from
the White system is allowed to pass to the photodetector.
But once each spectral scan at a prescribed wavelength, the mirrored
portions are rotated into the beam so as to block light from
the exterior and deflect that from the reference beam onto the
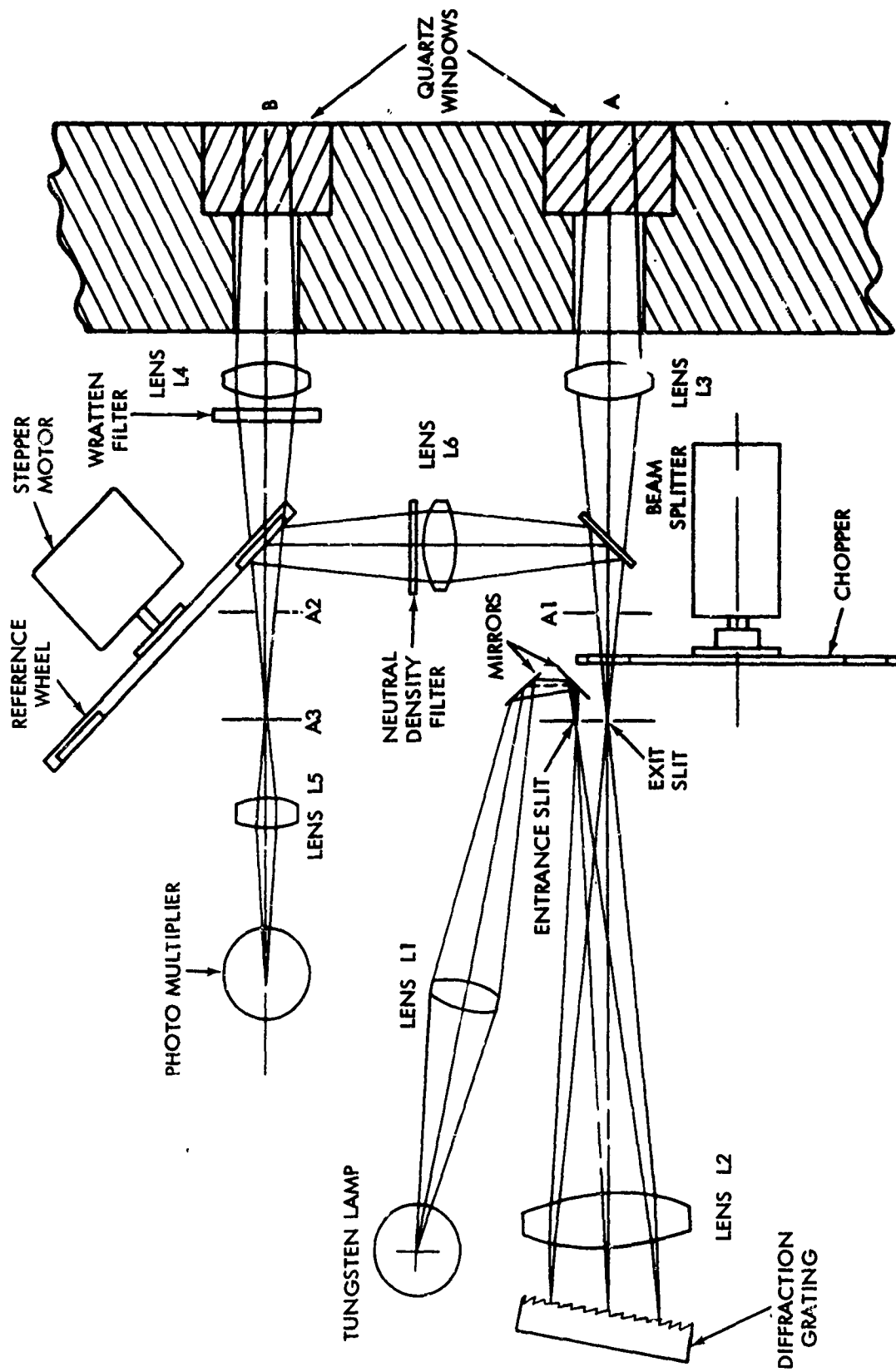sensor. Separate mirror segments of two different reflectivities

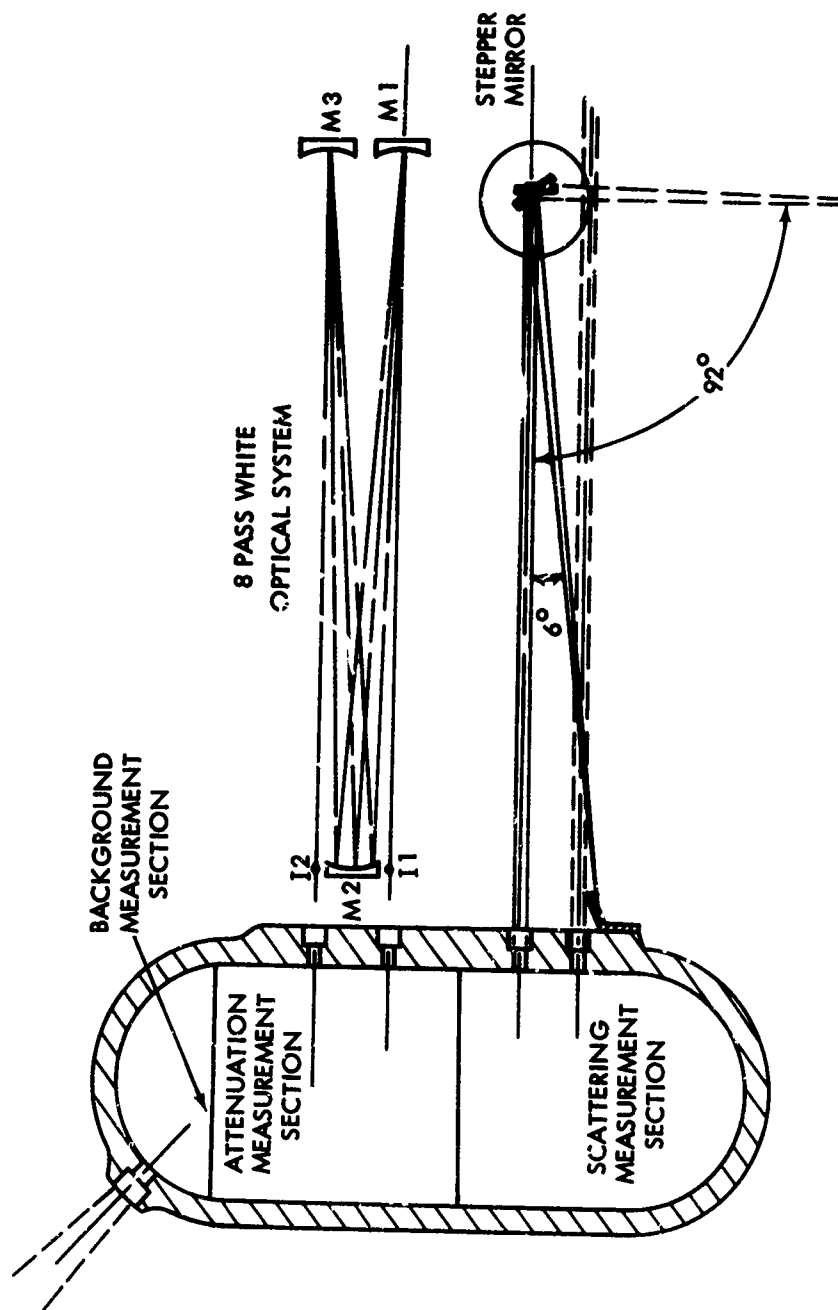FIG.6 SCHEMATIC OF ATTENUATION MEASUREMENT SECTION

3-4

FIG. 7 EXTERNAL OPTICS AND IN-SITU LIGHT PATHS OF THE THREE MEASUREMENT SECTIONS

roughly 0.80 and 0.18, provide reference signals differing in magnitude by a constant factor of about 4.5. This difference serves as a monitor of system gain during a measurement drop.

The scattering measurement section is designed to measure through angles from six to 92 degrees, the volume scattering function of ocean water for 435.8 millimicron wavelength light. This section is shown schematically in Figure 8. Radiation from the 100 watt Mercury short arc lamp producing an average brightness of 140,000 candlepower/cm^2 over the 0.31 mm arc diameter, is imaged one to one by lens L1 in the 0.50 mm diameter aperture A1. This aperture is imaged by lens L2, $f = 109.4$ mm, in the water at a distance of 1.92 meters which corresponds to twice the distance from the exit window A to the stepper mirror. Source light is deflected by the stepper mirror, Figure 7, which is attached to the motor shaft of a reversible deep sea stepping motor. The motor is programmed to scan in nine individual steps over a predetermined angular range and then return to the original angle at a rate of one complete cycle per minute. The angular deviation of the reflected beam from the incident beam varies from minimum of six degrees to 92 degrees as shown in Figure 7. At the minimum six-degree angle, the image of A1, seven mm in diameter in water, falls on the rear of a black mask attacked to the cylinder adjacent to the entrance window. This six-degree minimum angle is determined by geometrical considerations, such as the 962 mm distance to the stepping mirror, the 69.8 mm window separation, the image size, and the 20.6 mm free aperture of the window. The axis of the field of view of the optical receiver parallels at the 69.8 mm distance that of the source bundle. Aperture A2, 3.0 mm in diameter, located in the focal plane of collecting lens L4, $f = 90.7$ mm, determines the 33 milliradian circular field of view. Thus only flux scattered within the common volume of the reflected source beam and the solid angle subtended by aperture A2 and in the direction of A2 can enter the photo sensor compartment and contribute to the scattering signal. Accepted flux is reflected from 0.90 reflectivity beam splitter and filtered before falling on the cathode of an S11, 11 dynode photomultiplier. The interference filter which has a peak transmission of 65 percent and a half width of 11 mμ, passes only the 435.8 mμ line of the HG arc light. Since signal levels decrease by orders of magnitude as the scattering angle is scanned to larger angles, attenuation is required at the small angles in order to maintain a more nearly flat response. A filter wheel synchronized with the deep sea stepping motor, rotates appropriate neutral density attenuators into the light bundle within the receiver optics. As in the α section, a high and a low reference signal recorded during each cycle provide periodic checks on system sensitivity and gain. When the reference mirror wheel is positioned to intercept the source beam, lens L3 images L1 through an attenuating filter, the beam splitter, and the
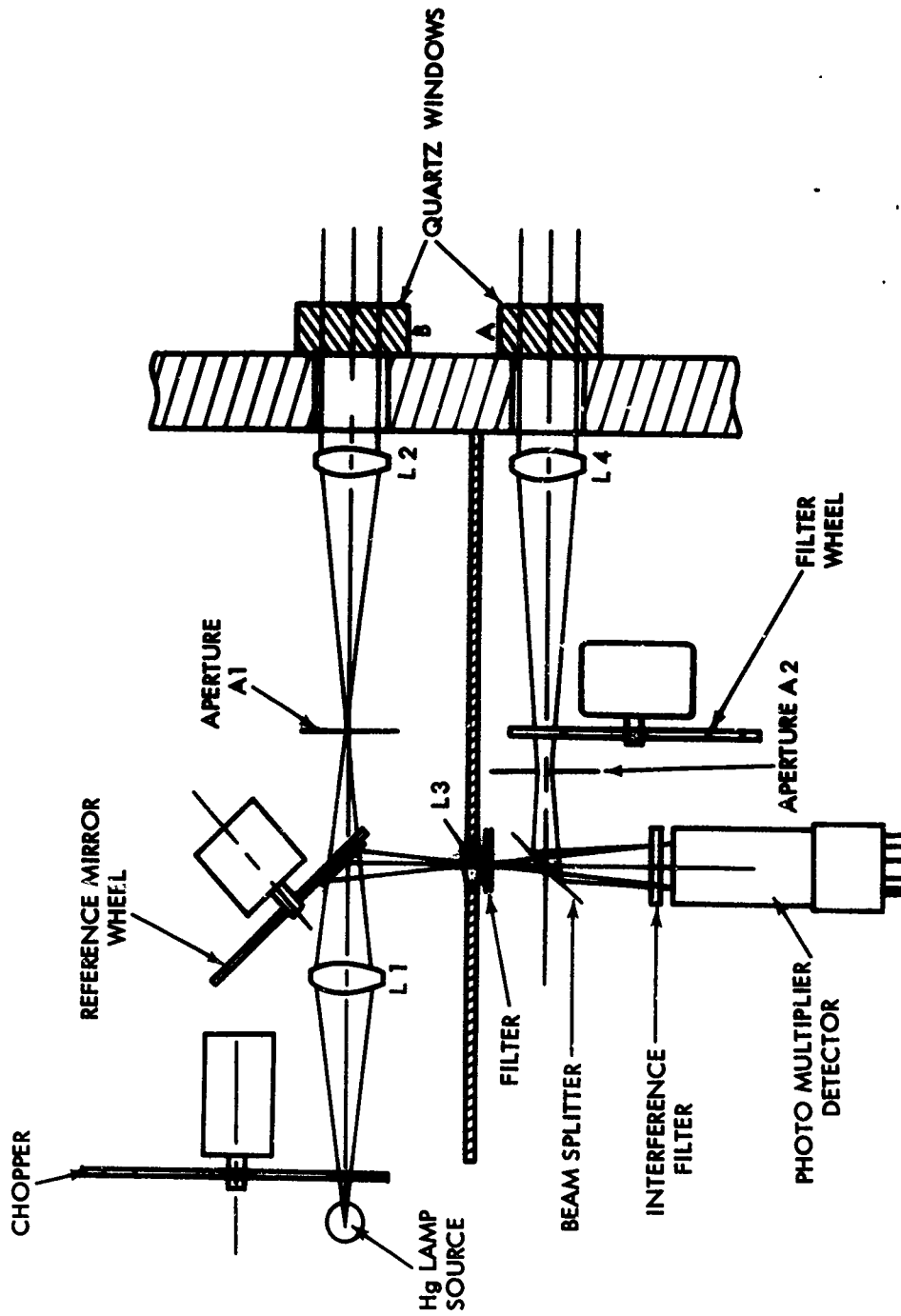
FIG.8 SCHEMATIC OF SCATTERING MEASUREMENT SECTION

interference filter onto the photocathode of the sensor. Here
again chopping is employed to facilitate background rejection
and signal processing.

The background measurement section is housed within one
of the hemispherical end caps of the optics cylinder. It is
a passive receiver of light from the submarine radiance
fields existing in the ocean. Accepted radiant flux is
restricted to a moderately small horizontally oriented solid
angle and to a narrow spectral band in the blue-green visible
region of the electromagnetic spectrum. The background section
is shown schematically in Figure 9. Light collected by the
82 mm focal length lens L1 is deflected by a 45 degree mirror
to the variable aperture A1 located in the focal plane
of L1. Aperture diameter is adjustable from 2.5 to 25 mm
permitting fields of view for the 82 mm lens from 2.3×10^{-4}
to 2.3×10^{-2} steradians in water. Lens L2 images the aperture
on the cathode of an S11, 11 dynode photomultiplier tube. The
interference filter passes a spectral band peaked at 485 mμ
and 20 mμ wide at the one-half transmission level while the right
angle prism serves simply to divert the light towards the
optical sensor. An opaque shutter positioned by a rotary
solenoid blocks incoming flux for a duration of five seconds
out of every minute thus providing a zero signal level.

Solid state electronics employing operational amplifiers
with logarithmic outputs are used to process signals from the
three optical sections. Amplifiers are matched with photo-
multiplier current outputs which are linear from the noise
level, about 10^{-7} amp, to saturation at about 10^{-3} amp, or
over a dynamic range of 10^4. Multiple decade log amps are
required for the background and scattering section, because
their output currents may encompass the full dynamic range.
The α section however manages with a two-decade range. Direct
current outputs from the log-amps are then recorded on a light
beam galvanometer recording oscillograph. Frequency responses
for the three recorded signals from the attenuation, scattering,
and background sections are respectively 120, 120, and 30 hertz.

Two equipments, a Ramsay Mk XI Deep Sea Probe and a Hydro
products Abyssal pinger are attached externally to the pressure
housings on the DOOM package. The Ramsay Probe simultaneously
measures temperature and pressure to depths of 33,000 feet
and converts these parameters to DC voltages. Temperature
over a range from 0 degrees to 35 degrees is sensed by two
thermistors connected in a DC bridge circuit. The pressure
sensor is a 0 to 15,000 psi silicon strain gauge pressure
transducer manufactured by Fairchild. A deep sea cable from
the instrument sphere provides external power for operating
the instrument and permits recording of sensor outputs in
the sphere. The abyssal pinger is a self-contained unit
providing 13 watts of peak acoustic power in pulses two
milliseconds in length and at a frequency of 12 kilohertz.

COLLECTING
LENS L1

FRONT SURFACE
MIRROR

ROTARY
SOLENOID

VARIABLE
APERTURE

OPAQUE
SHUTTER

LENS L2

PHOTOMULTIPLIER

INTERFERENCE FILTER

RIGHT ANGLE
GLASS PRISM
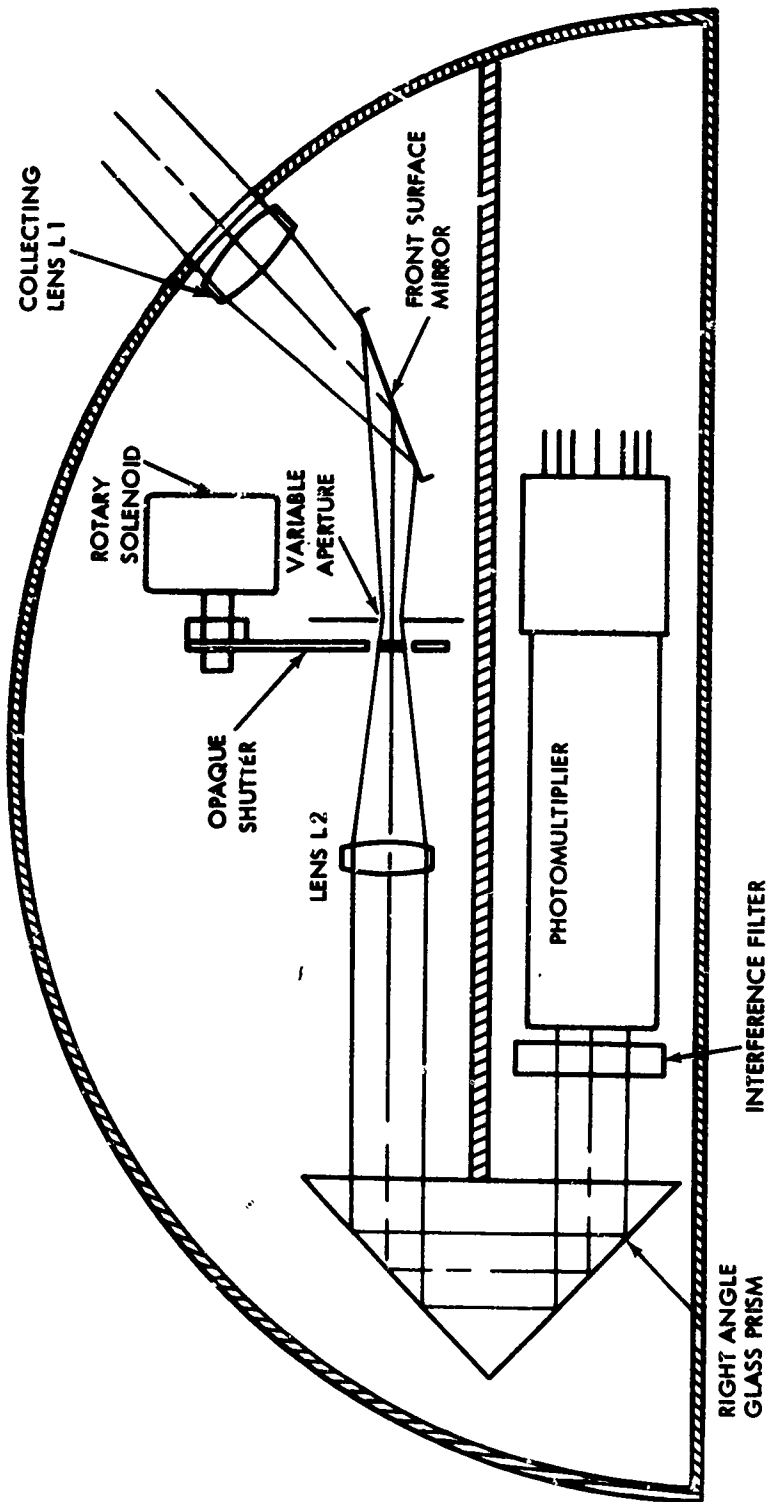
FIG.9   SCHEMATIC OF BACKGROUND MEASUREMENT SECTION

Pulse repetition rate is chronometer controlled at one pulse (ping) per second. The difference in time of arrival of the directly transmitted pings and those reflected from the bottom are recorded on the ship's conventional 12 Khz depth sounder and the resulting trace separation provides the means for determining the distance of the package off the bottom.

Power for the DOOM instruments is supplied by two rechargeable silver zinc batteries. The primary voltage at 28 VDC is used both directly and after conversion to regulated AC and DC voltages, i.e., 115 VAC, $\pm$ 15 VDC, 1200 VDC, etc. A separate 40V battery provides power for the mercury arc lamp. An internal timer automatically turns the system off after a maximum three-hour operating period as determined by the capacity of the batteries.

Seven channels of analog information are simultaneously recorded by a D. G. O'Brien, model 300 light beam galvanometer oscillograph on 3 5/8-inch photosensitive paper. These seven data channels consist of the three optical signals, the Ramsay probe outputs of pressure and temperature, a timing marker at two-second intervals, and a static reference trace provided by a fixed mirror.

Chapter 4

CALIBRATION AND DATA REDUCTION

Both spectral attenuation and volume scattering measurements are quantitative determinations of their respective coefficients while the background data are strictly relative in nature. The α measurement is dependent upon the accurate relative measurement of the difference in received optical power for two cases, (1) when the attenuation is essentially zero, which occurs in air and (2) when the system is submerged in the attenuating medium. The scattering measurement requires a determination of the total power in the source beam relative to that received when in the scattering medium. Thus in the α and s sections a calibration standard is not required since both sections contain their own sources of radiation and calibration involves only an accurate comparison of signals under two different conditions. Such is not the case for the background section which acts solely as a passive receiver of external light. Hence a standard radiation source would be required for an absolute quantitative calibration. Due to the difficulty of obtaining and operating such a standard in the field, in this case on a rolling spray-lashed deck at sea, only qualitative data on background lighting is recorded.

The quantitative α calibration is made by comparing the respective radiant power, P_A and P_W transmitted through the two media, air and water. The power returning to the cylinder in the air case is

$$P_A = P_o \, T_{QA}^2 \, \rho_m^7 \, e^{-\alpha_A x}$$

where P_o is the source power leaving the cylinder, T_{QA} is the transmittance of the quartz-air interface, ρ_m is the reflectivity of the folding mirrors, α_A is the attenuation coefficient in air, and x is the external path length. Since attenuation in air is negligible the exponential term approaches unity and the equation becomes

$$P_A = P_o \, T_{QA}^2 \, \rho_m^7$$

Recorder deflection produced after logarithmic amplification is

$$D_A = 1/B \, \log k \, P_A$$

where B is the slope of the logarithmic gain curve and k is a constant, involving receiver responsivity. For the water case

$$P_W = P_o \, T_{QW}^2 \, \rho_m^7 \, e^{-\alpha x}$$

where T_{QW} is the transmittance of the quartz-water interface, α is the attenuation coefficient of water, and

$$D_W = 1/B \, \log k \, P_W$$

The difference in received signals for the two cases is

$$\Delta D = D_A - D_W = 1/B \, \log \frac{P_A}{P_W}$$

Substituting for the received powers

$$\Delta D = 1/B \, \log \left(\frac{P_o \, T_{QA}^2 \, \rho_m^7}{P_o \, T_{QW}^2 \, \rho_m^7 \, \ell^{-\alpha x}} \right) = 1/B \, \log \left[\frac{T_{QA}^2 \, \ell^{\alpha x}}{T_{QW}^2} \right]$$

since the reflectivity of the front surface mirrors overcoated with SiO is the same in air as in water. Solving the above equation for α

$$\alpha = \frac{2.303}{x} \left[\log \left(\frac{T_{QW}}{T_{QA}} \right)^2 + B\Delta D \right]$$

Substituting applicable values for the DOOM system, $T_{QW'} = .9980$, $T_{QA} = .9644$, and $x = 7.444$ m, then

$$\alpha = 0.0092 + 0.3094 \, B\Delta D \, m^{-1}$$

To calculate the magnitude of α, it is only necessary to measure the difference in deflection for the two cases and to determine the slope of the gain curve of the log amp. This curve, a plot of relative source power versus recorder deflection is obtained by attenuating the source light with calibrated

neutral density filters. A typical gain curve linear
over approximately two decades is shown in Figure 10.

A characteristic of a grating monochrometer is that
the spectral dispersion is a linear function of wavelength.
The DOOM grating is driven by a precision 18 step cam.
From an accurate physical measurement of the radii of the
cam steps and the length of the lever arm drive, the wavelength
interval between steps can be accurately calculated. Quantitative
setting of wavelength is accomplished by adjusting the grating
angle until the 54 6.1 mμ line of a H$_g$ lamp is passed through the
exit slit for a specified cam step.

The scattering section measurement consists of measuring
and recording a known portion of the total power of the source
radiation leaving the cylinder and comparing it with that which
is scattered by the water into the solid angle subtended by
the optical sensor. Calibrating apparatus for determining
source power is shown in Figure 11. A glass right angle prism
is temporarily secured on the outside of the cylinder across
the two quartz windows so that the source beam is deflected into
the receiver optics in such a way as to pass geometrically the
total source beam. Neutral density filters provide appropriate
attenuation to prevent saturation of the photomultiplier.
The power measured is

$$P_{CAL} = P_o \, T_{AQ}^2 \, T_{GA}^2 \, T_F$$

where P_o is the power leaving the cylinder, and T_{AQ}, T_{GA},
and T_F are the transmittance respectively of the air-quartz
interface, the glass-air interface, and the attenuating
filter. The recorder deflection produced is

$$D_{CAL} = 1/B \, \log \, (k \, P_{CAL})$$

where B is the slope of the log amp gain curve and k is a
system responsivity constant. Scattered power collected
by the optical receiver when submerged in water is

$$P_w = P_o \, \sigma(\theta) \, C(\theta, \, \alpha) \, T_{wQ}^2 \, \rho_m$$

where $\sigma(\theta)$ is the volume scattering function, T_{wQ} is the
transmittance of the water-glass interface, ρ_m is the
stepper mirror reflectivity, and the function $C(\theta, \, \alpha)$ is
given by the equation

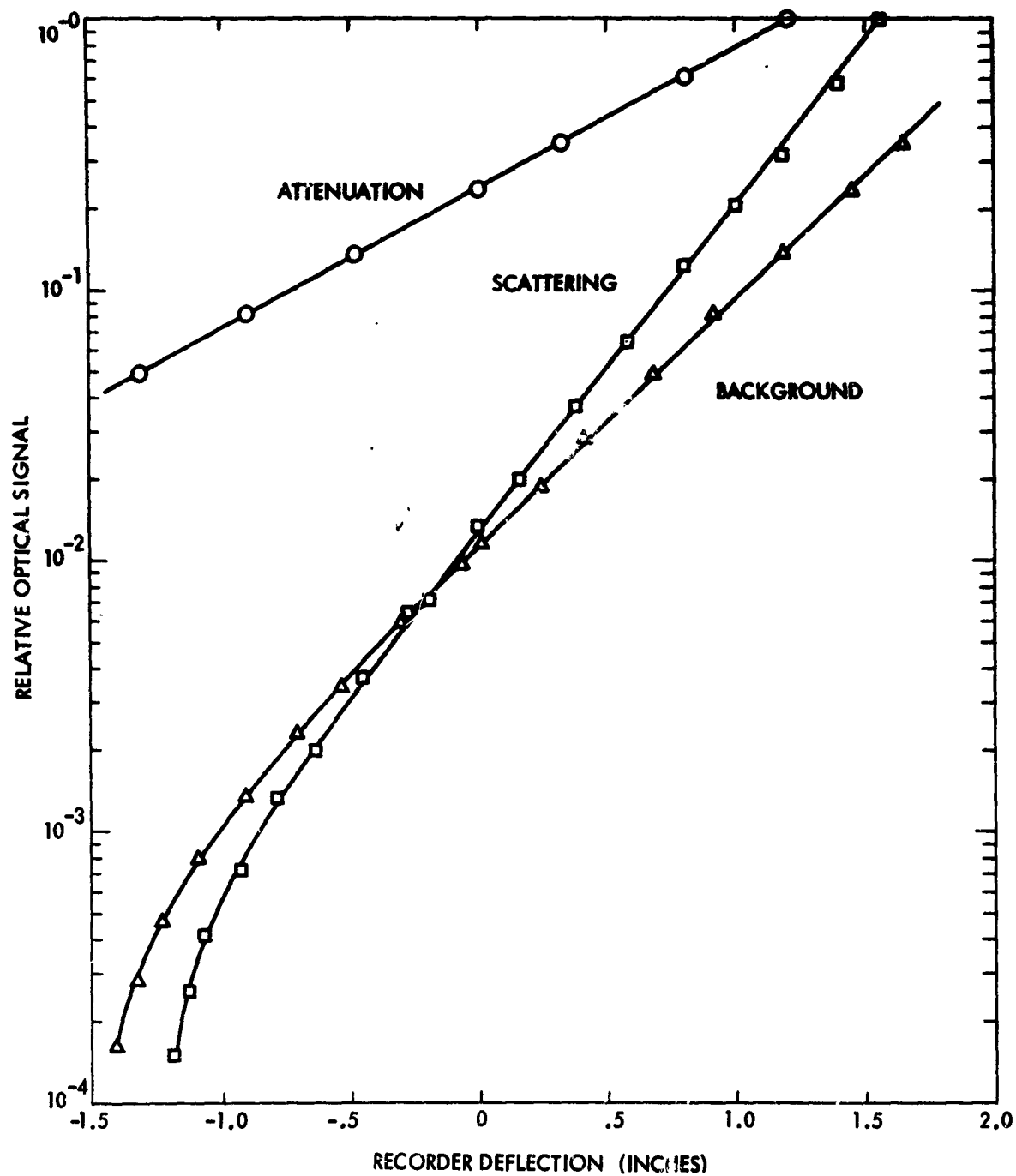$$C(\theta, \, \alpha) = \ell^{-\alpha(2b \, - \, a \, \cot \, \theta \, + \, a \, \csc \, \theta)} \int_\Omega dx/\sin \, \theta$$
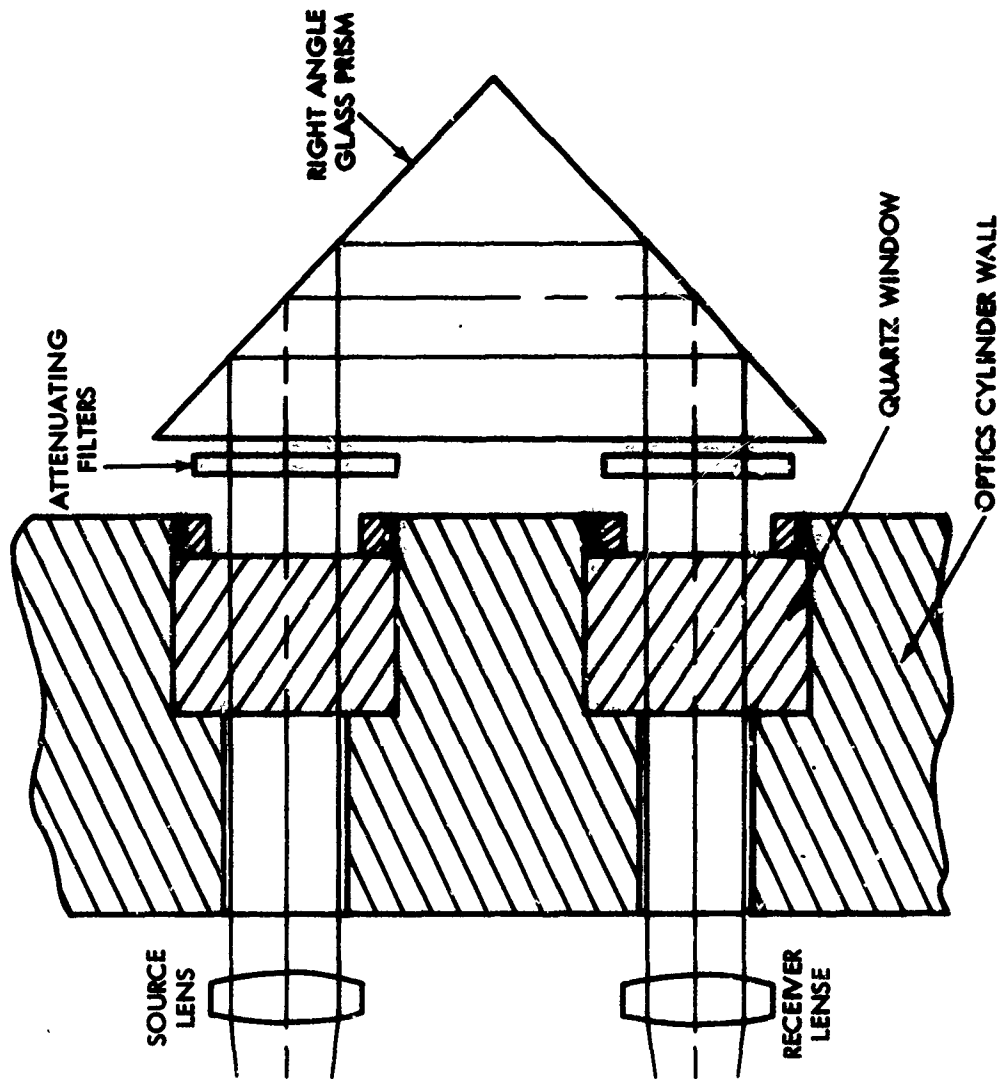
FIG.10 GAIN CALIBRATION CURVES FOR THE THREE MEASUREMENT SECTIONS

FIG. 11 SCATTERING SECTION CALIBRATION OPTICS

The exponential term gives the attenuation loss over the traversed water path as determined by the scattering geometry, b being the distance to the stepper mirror and a the window separation. The integral computes the portion of the flux from the intercepted length of source beam (dx) falling within the solid angle (Ω) of the receiver that is collected by the optical sensor. Deflection produced by the scattered light is given by

$$D_w = 1/B \log (kP_w)$$

Subtracting the two deflections

$$D_{CAL} - D_w = \Delta D = 1/B \log \frac{P_o \, T_{AQ}^2 \, T_{GA} \, T_F}{P_o \, \sigma(\theta) \, C(\theta, \alpha) \, T_{wQ}^2 \, \rho_m}$$

and solving for $\sigma(\theta)$ yields

$$\sigma(\theta) = \frac{T_{AQ}^2 \, T_{GA}^2 \, T_F}{C(\theta, \alpha) \, T_{wQ}^2 \, \rho_m} \, 10^{-B\Delta D}$$

Substituting values for the constants $T_{AQ} = .9642$, $T_{wQ} = .9980$, $T_{GA} = .9561$, $T_F = 1.71 \times 10^{-5}$ and $\rho_m = 0.89$, we obtain

$$\sigma(\theta) = \frac{1.64 \times 10^{-5} \, 10^{-B\Delta D}}{C(\theta, \alpha)}$$

To obtain the volume scattering function the relative difference in recorder deflection must be measured, the gain slope determined, and $C(\theta, \alpha)$ evaluated as a function of the scattering angle. The gain curve of the log amp, also obtained by using calibrated neutral density filters, is linear over a range of three decades as shown in Figure 10. The value of α in the exponential term is obtained from the α measurement section and the integral of the solid angle is computed from the geometry and optical parameters of the system.

Since the background measurement is qualitative and passive in nature, its calibrations consist of those dealing with the response of the sensor system to external stimuli. System gain as measured using a tungsten source and calibrated neutral density attenuators, is linear over about three decades as shown in Figure 10. Frequency response is determined by chopping the source radiation with a continuously variable speed motor. Signal level was down by 1/e at about 30 hertz.

All data, both calibration and in-situ measurements, are recorded on seven channels of the DGO oscillograph.

Presented in Figure 12 are oscillograph traces of a
calibration in air. Traces A and B, the pressure and
temperature signals are inactive. A one minute record is
presented which includes a complete scattering measurement,
trace C, from 6 degrees to 92 degrees and two transmission
spectra, trace D, one with high, the other with the low
reference signals. Trace E is the dummy trace and trace F the
timing marker producing pips at two second intervals. The
background section is shuttered, so its signal, trace G,
represents the dark current noise of the photomultiplier
and associated electronics. The transmission spectra
consisting of 20 cam intervals of 1.5 second duration each,
are scanned at a rate of two per minute. Transmission data
are recorded at 18 wavelengths, starting with the longest
at step $\lambda 20$ and driving to the shortest at step $\lambda 2$. Step
$\lambda 12$, at the same wavelength as step $\lambda 11$, is used for the
reference signal and step $\lambda 1$ recycles the cam to the initial
wavelength $\lambda 20$. The high reference signal (HR) is about
a factor of 4.5 greater than the low reference (LR).

The 60 second scattering measurement cycle includes
in addition to the nine angular measurement signals, a
shuttered zero level signal (SHUT) and both high (SHR) and
low (SLR) reference signals all of which are recorded as the
stepper recycles back from the maximum 92 degree angle to
the initial 6 degree angle. During calibration as in Figure 14,
a constant radiant flux enters the receiver optics during
the 47 second period alloted for angular measurements. At
the two smallest angles, 6 degrees and 13.2 degrees, attenuators
of the filter wheel attenuate the flux by factors of 0.11
and 0.33 respectively. The high and low reference signals
differ by a factor of about ten. It should be remembered
when viewing these records that the output signals of the three
measurement sections have been logarithmically compressed.

An in-situ record is shown in Figure 13. Trace
identification and signal notation are the same as for the
previous calibration data, that is, A is the pressure
signal, B temperature, C scattering, D-α, E-dummy, F time
marker, and G background. Temperature and pressure
transducers are functioning; the temperature near its
maximum at about 25°C, the pressure reading very nearly
atmospheric. In this case the package is near the surface,
so attenuation is moderately high; the coefficient in the transmission
window at $\lambda 11$ (480 mμ) being about 0.070 m^{-1}. Scattering
signals are also large and difference in signal levels at
the nine angles are easily recognized. The background signal
is riding at the noise level of the photomultiplier indicating
an absence of luminescent spikes and an illumination level
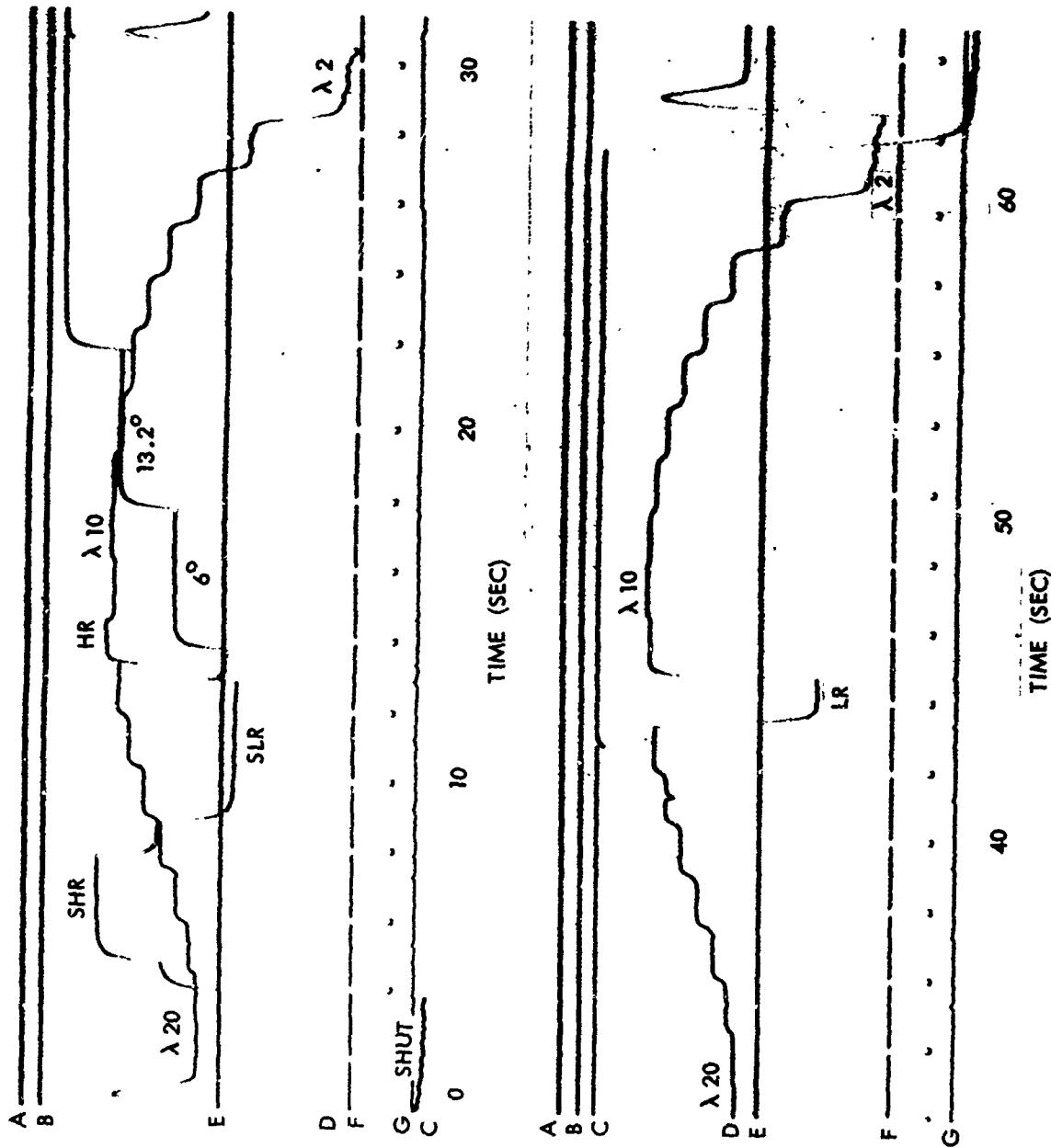characteristic of a very dark night.
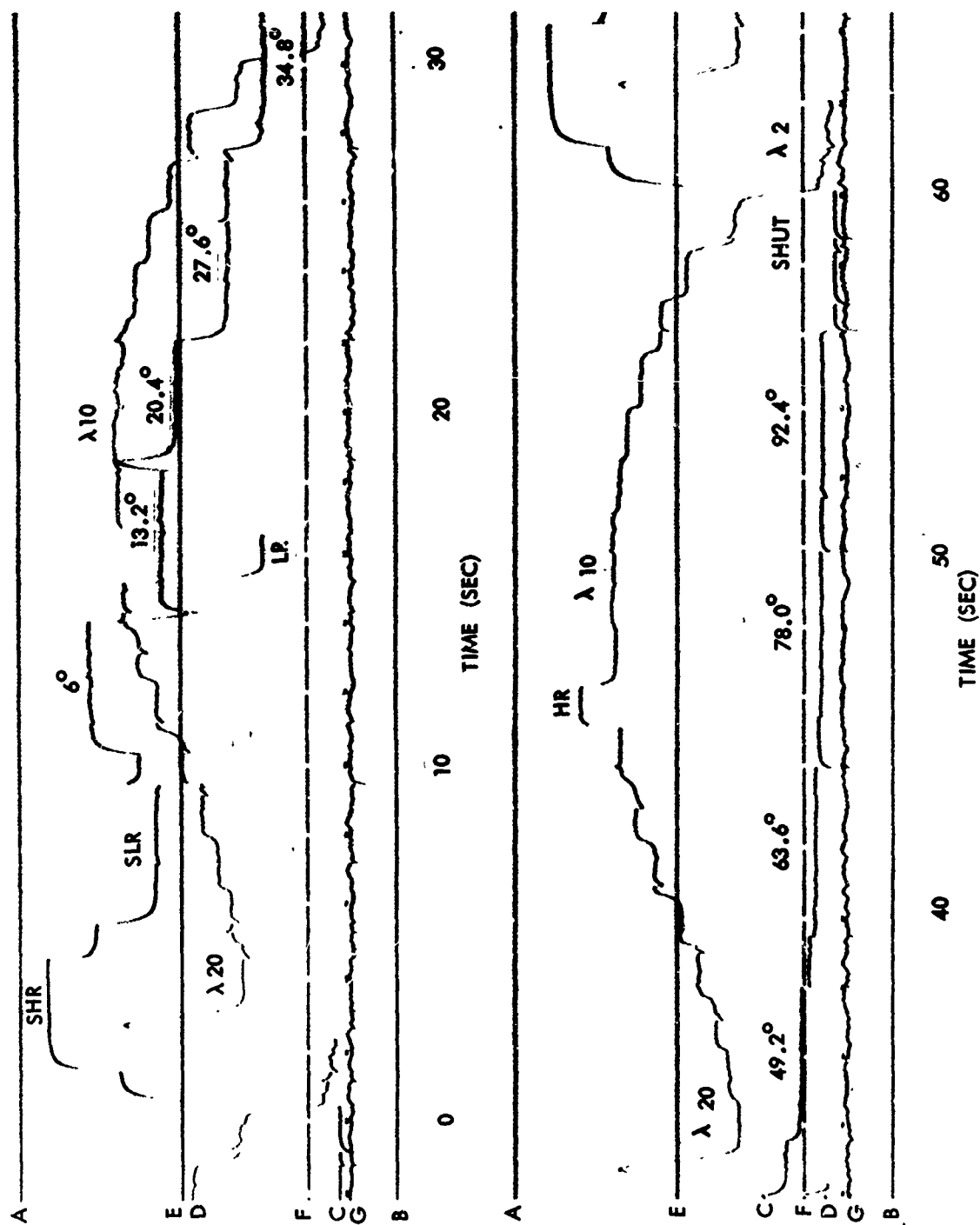
FIG.12 RAW DATA FROM IN-AIR CALIBRATION RUN

FIG. 13 RAW DATA FROM AN IN-SITU MEASUREMENT RUN

Chapter 5

OPERATIONAL PROCEDURES

DOOM operations are conducted from aboard Auxillary
~l Oceanographic Research (AGOR) ships which are under
ι :echnical control of the U. S. Naval Oceanographic Office.
The · ships are equipped with conventional instruments for routine
ocea. ιgraphic studies and provide support for programs of the
several east coast Naval Laboratories. A three ship east coast
fleet consisted of the U. S. Naval Ships (USNS) GILLIS, SANDS,
and LYNCH, T-AGOR's four, six, and seven respectively, prior
to the de-commissioning of the GILLIS in the fall of 1969.
Project DOOM has operated for both the GILLIS and the LYNCH,
the latter being shown in Figure 14. The LYNCH, a 1320 ton
displacement, 209 feet long vessel, has a cruising range of
12,000 nautical miles at a maximum speed of 12 knots and can
accomodate a scientific party of 15.

Shipboard installation involves bolting the DOOM assembly
to the deck under the A-frame located on the fantail,
Figure 15, where it is secured at all times other than during
actual measurement drops. The A-frame serves to lift and swing
the package outboard for drops and for lifting the top half
of the sphere for data removal and daily maintenance. Either
of two winches may be used, a deep sea winch containing
45,000 feet of tapered 3/8 inch to 3/4 inch steel wire rope
or the intermediate winch utilizing 30,000 feet of 1/2 inch
steel wire rope. In order to provide an adequate safety factor,
for oceanographic work a factor of 2.5 is considered sufficient,
the deep sea unit must be used for depths in excess of 16,000 feet.

Operations at sea may be divided into three phases:
(1) Pre-drop preparations and calibrations, (2) the measurement
drop, and (3) post and between drop activities. The system,
of course, has been completely checked out, calibrated and sealed
in the laboratory prior to shipment to the port of embarkation.
Either en route to or upon arrival at the first measurement
station, the top of the instrument sphere is removed and the
system connected for operation on external power. Performance
tests on the entire system are conducted on external power and
adjustments are made if necessary. Batteries are tested,
fresh film is loaded in the recorder, and the interval timer
which determines the length of operation is set. The system
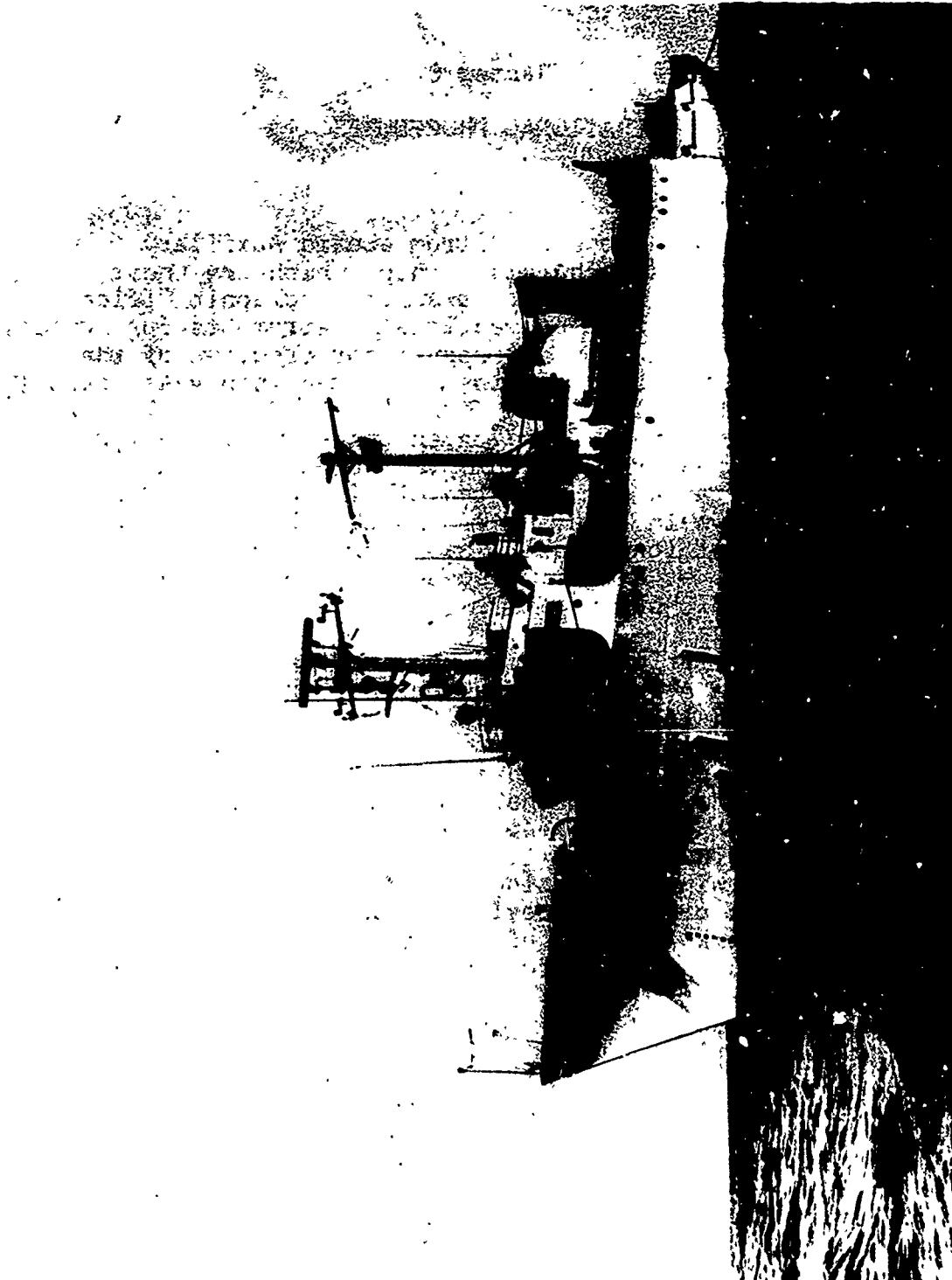is now switched to internal power and the following calibrations

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FIG. 14   THE U.S. NAVAL SHIP LYNCH. T – AGOR – 7
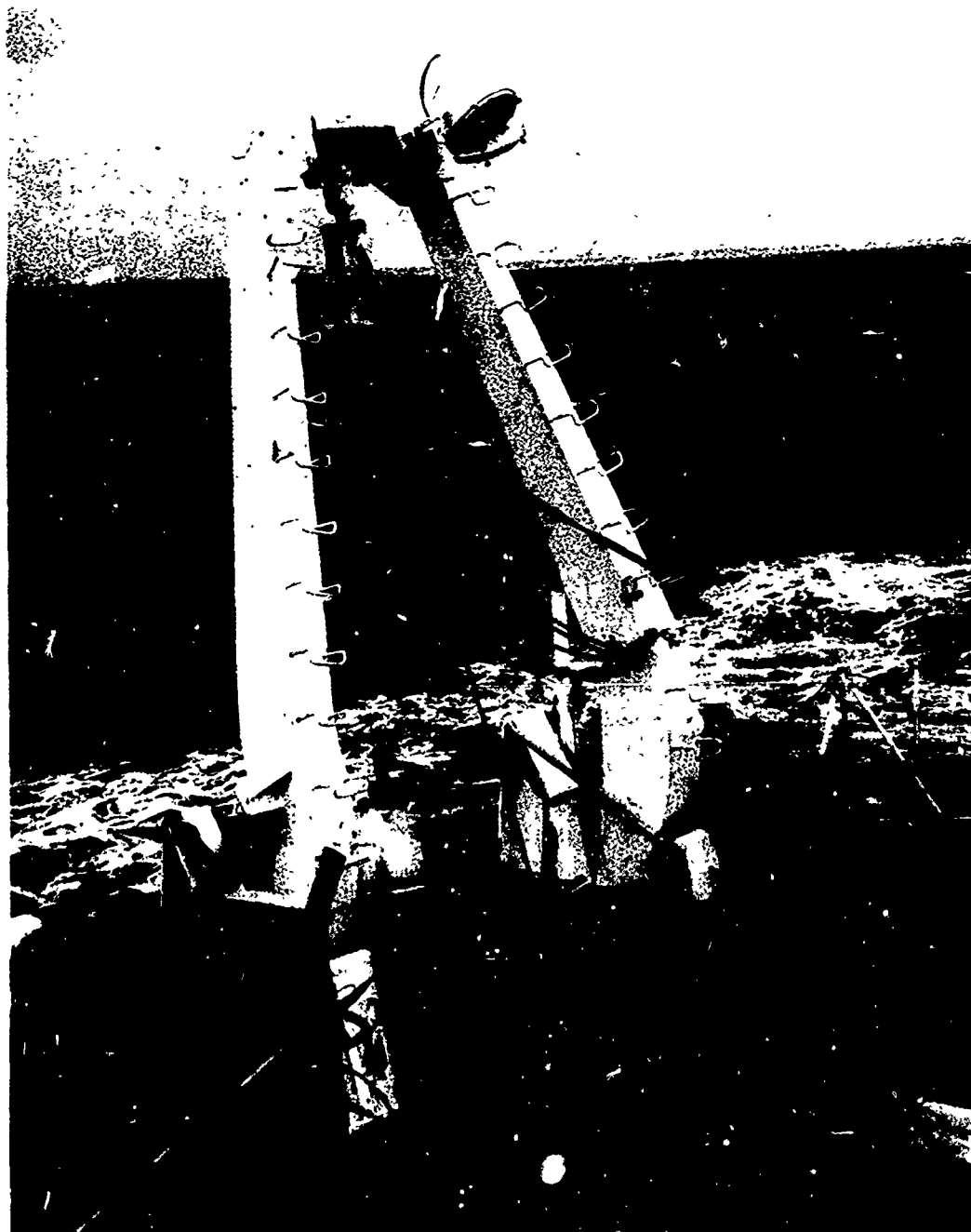
FIG. 15   DOOM ASSEMBLY AT SEA

are run and internally recorded:

(1) the attenuation section air calibration,
(2) the attenuation section gain calibration with appropriate neutral density filters,
(3) the scattering section calibration.

After this five to six minute calibration period, the system is shut down, the top of the sphere replaced, and DOOM is ready for the second operational phase, the measurement drop.

Because of the high ambient light levels during the day which tend to saturate DOOM's optical sensors, drops are made during the hours of darkness. Prior to each drop a bathythermograph (BT) is taken and examined for strong or rapid variations in the vertical thermal structure of the surface waters (to 1000 feet). Knowledge of the existance and depth of such thermal gradients are of value when planning a drop because they usually correspond to significant changes in optical characteristics. Both the DOOM system and the pinger are now started by mating electrical connectors located external to their pressure housing. After a short warm up period, and visual inspection of the light beams emanating from the cylinder, DOOM is hoisted and swung over the side into the water. Lowering rates, variable from about six to 70 meters per minute for the DOOM package, and length of wire out are constantly monitored from on-deck indicators. Very slow lowering rates with momentary stops are incorporated when it is suspected that the waters are so layered that small changes in depth will produce rather major changes in the optical signals. However, when a deep measurement is planned, lowering rates must be fast enough to place the package on the bottom within the time limit, a maximum of three hours, set on the interval timer. In the ship's laboratory, acoustic signals from the DOOM pinger and the ship's fathometer are recorded on a precision depth recorder. Two signals are received from the DOOM pinger, one propagated directly from the package to ship, and the other after reflection off the bottom and then to the ship. By measuring the difference in time of arrival of these signals, the distance of the package off the bottom is computed. This computation is used to stop the package at some height off the bottom, anywhere from 0 to 100 meters depending on factors such as sea state, wire angle, and bottom topography. After automatic shutdown of the DOOM instruments, the package is retrieved and secured on deck.

Post recovery operations consist of opening the instrument sphere, removing the recorder magazine with the data, and placing the batteries on a 12 hour charging cycle. An air calibration is deferred at this time until the next drop so that external mirrors may be cleaned and dried. The data recorded on photosensitive linowrit paper is developed and printed at sea. A cursory analysis of this data is made to determine if the DOOM instruments functioned properly during the drop.

If the discrepancies are found, remedial repairs are made
prior to the next evening's drop. Data are also examined
for unique optical phenomena which would warrant further
investigations and thus could be programmed into succeeding
drops.

Factors determining the length of the total operational
cycle are the 12 hour battery charge, the three to six hour
measurement drop, and the constraint imposed by the night
operation requirement. These factors combine to place DOOM
operations on a 24 hour measurement cycle. Ship time when
the DOOM package is not in the water may be spent steaming
to a new station. Or it has been used by groups from other
Navy Labs and universities on Navy contracts who "piggyback"
and conduct independent research on a not-to-interfere basis.

Chapter 6

SEA TRIALS

The first successful sea trials of the DOOM system were
conducted aboard the USNS GILLIS in December of 1967 in an
operating area south of the Bermuda rise. Five subsequent
cruises to various areas of the Atlantic, Table II, have
resulted in a total of 39 measurement drops at 29 different
stations as indicated in Figure 16. Measurement areas include
coastal waters of the Virginia Capes, and East Florida, the
basins of Northwest and Northeast Providence channels, the
Gulf Stream in the Florida Straits, off the Virginia Capes,
and further out at sea off New Jersey, the deep basin waters
of the Hatteras Abyssal plain from the Bahamas north to New York,
and the trench area from Cuba to Puerto Rico.

Cruises are nominally scheduled for about two weeks
duration with perhaps 10 to 12 drops at from five to six stations.
The remainder of the time is allowed for transit from port
to stations, computed at the ships cruising speed of 10 knots.
The number of drops per cruise has been generally less than
scheduled due to a variety of reasons falling in three
broad categories; (1) inclement weather (2) equipment failures,
both DOOM and ship and (3) logistic difficulties. In order to
prevent damage to or loss of the DOOM package during launch,
lowering, or recovery, operations are conducted only when moderate
to fair sea conditions prevail. Rough seas have restricted to some
extent operations on all cruises. DOOM equipment failures
have included the shorting of conductors in the deep sea
cables, flooding of external electrical connectors, and a
burnt out power inverter. The loss of a main engine and
chronic problems with winches constitute the major ship
equipment failures.

Each of the six DOOM cruises will be discussed separately
below with regard to dates, areas, drops, data obtained and
problems. Cruises are denoted chronologically by letter, the
drops by number. Drop C5 would thus be the fifth drop of cruise
C, the third cruise.

Cruise A departed Norfolk on 7 December 1967 aboard the
GILLIS and after steaming through heavy seas arrived on station
about 100 nautical miles south of Bermuda on 11 December 1967.
Three drops were completed here in 4570 meters of water before

Cruise	Dates	Number of Stations	Drops	Operating Area
A	12-7-67 to 12-18-67	3	5	100 to 200 nautical miles southeast of Bermuda
B	9-15-68 to 9-27-68	4	6	450 nautical miles off New Jersey coast in and near the Gulf Stream
C	11-26-68 to 12-3-68	5	6	Florida Straits, Bahama Channels, and Atlantic Ocean just east off islands
D	3-17-69 to 4-2-69	6	6	Florida Straits, Bahama Channels, and Atlantic just east of islands
E	10-17-69 to 10-31-69	5	6	Virginia Capes, Coastal Area and Hatteras Abyssal Plain from 37N, 73W to 27N, 72W
F	1-6-70 to 1-20-70	6	10	Bahamas and south to Puerto Rico trench

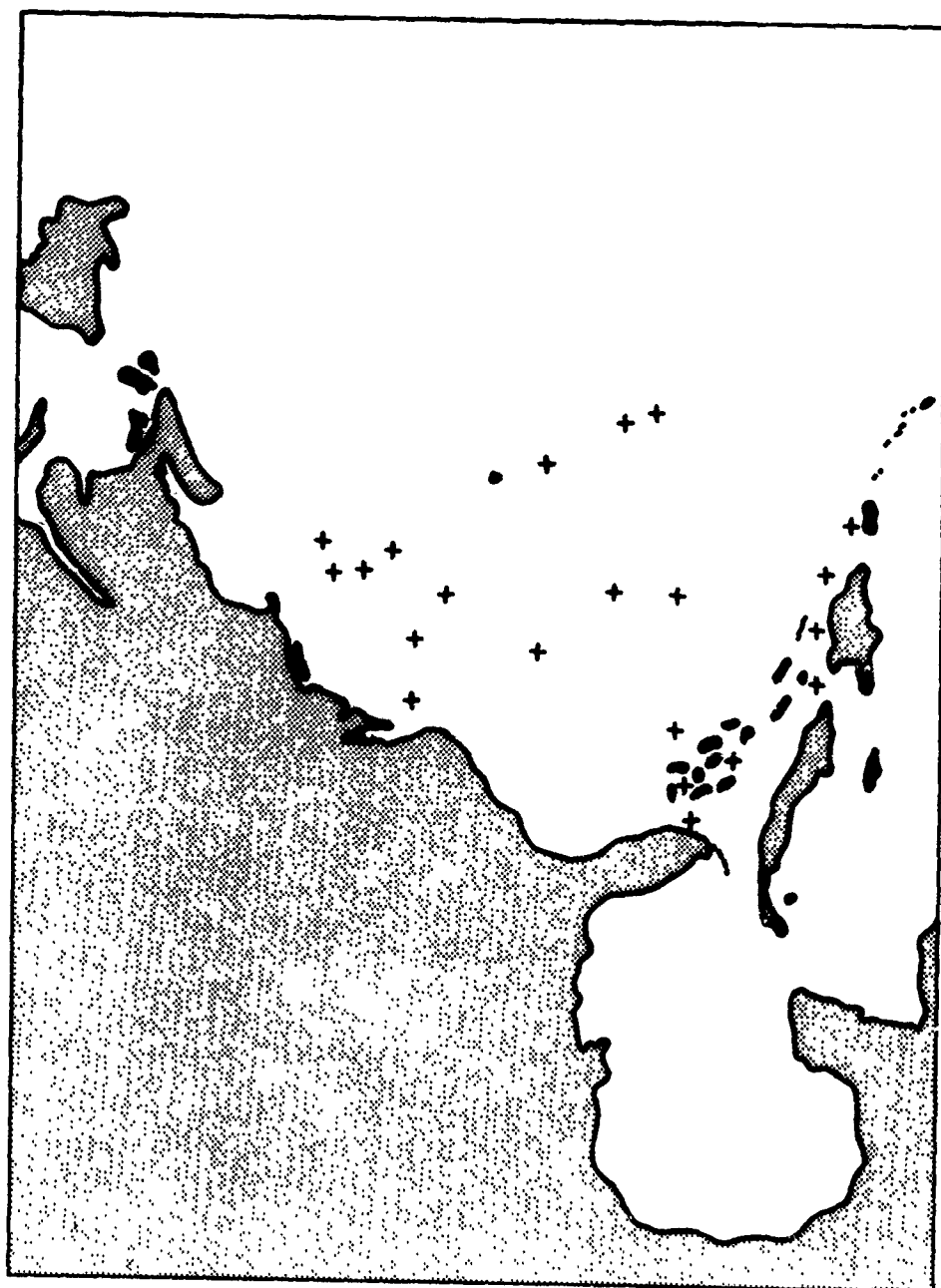TABLE II.   DOOM Measurement Cruises December 1967 to January 1970

FIG. 16 DOOM MEASUREMENT STATIONS THROUGH JANUARY 1970

transiting on 14 December 1967 about 120 miles southeast
to deeper water (5300 meters) where two more drops were made.
A major storm blew up during the evening of the 15th forcing
us to abandon the measurements and run for Bermuda, arriving
on 18 December 1967.

The scattering section had not been completed in time
for Cruise A so only spectral attenuation and background
measurement were attempted. The first drop made in daylight
resulted in receiver saturation due to the high ambient light
levels for both α and background signals when the package was
near the surface. It was then decided to make all subsequent
measurements at night. Further trouble developed during drop
Al at a depth of 800 meters when two cable conductors, carrying
the background signal and +15 VDC between cylinder and sphere,
were shorted, thus driving the background trace off scale on
the recorder. Unfortunately this short developed only under
large hydrostatic pressure so the source of this difficulty
eluded us until after drop A3 when the short persisted after
DOOM was surfaced. Luckily only these two conductors of the
16 in the cable were shorted. Therefore we were able to switch
their signals to spare conductors allotted for the inactive
scattering section and the background section was functioning
again. Another casualty of DROP Al was the pressure temperature
probe which failed to function because of electronic problems
in its regulated DC power supply. Repairs were trivial and the
probe performed satisfactorily for the remainder of the cruise.
In drop A3 during launch, the package was inadvertently slammed
against the side of the ship which resulted in a shift of the
α section within the cylinder and a misalignment with the external
optics. Thus α data on this drop was lost.

Although a number of problems had developed during
cruise A, it was felt that a reasonable amount of worthwhile
data had been obtained. Spectral attenuation measurements
had been moderately successful on all but drop A3, and
significant background data was obtained on drops A4 and A5.
However, reduction and analysis of this data back at the
laboratory revealed that signals became markedly non-linear
as the drops progressed resulting in an apparent decrease in
α as a function of operating time. This effect is quite
evident when curves of attenuation coefficients are plotted
versus depth both as the package is lowered and then raised
to the surface. One would expect the "up" curve to essentially
retrace the "down" curve. However, this does not occur.
The measured attenuation continued to decrease after the bottom
had been reached and the "up" curve tracked at a level
appreciably below the "down" curve. Study of the non-linear
effects failed to reveal the exact nature of the problem other
than possible variations in amplifier gain as a function of
temperature. Since cruise A data is subject to these errors,
neither quantitative nor qualitative calculations of attenuation
coefficients could be made with any degree of confidence.

A temporary manpower shortage, created when personnel were assigned to an urgent short term project, did not permit a thorough investigation of the DOOM electronic problems prior to the next cruise in September 1968, nor did it permit the completion of the scattering section. Some minor modifications were made on the electronics but it was not really expected that these would eliminate the non-linear effects. However, certain tests in-situ at sea were planned which, it was hoped, would shed some light on these difficulties. These were mainly concerned with the effect of temperature changes within the DOOM package which are induced by the inherent nature of the thermal structure of the ocean where temperature drops to near feezing at the ocean bottom. To minimize cooling effects, shallow drops were planned in the warmer surface waters. Deep drops would be made for comparison. Even if electronic problems recurred at depth, data of value would be obtained from the surface water measurements.

Cruise B was originally scheduled to depart Norfolk, Virginia on 13 September 1968 and operate at seven different stations from the shallow waters off the Virginia Capes to the depths of the abyssal plain some 450 miles east of New York, before returning to port at Bayonne, New Jersey on 27 September 1968. A group from the Naval Ammunition Depot, Crane, Indiana would piggyback on this cruise in order to test submarine markers for the USS DOLPHIN. At the last moment the port of embarkation was switched to Bayonne where sailing was delayed by two days until the 15th due to a breakdown of one of the ships two main engines. Rough seas further delayed DOOM operations until the night of 20 September 1968. Since clearances to operate in Fleet Areas must be secured well in advance of planned operations, tests at the first three stations scheduled prior to 20 September had to be abandoned. Six drops were then made on successive days at stations about 450 nautical miles off the east coast, on both sides of and in the Gulf Stream. The ship, again the GILLIS, returned to port on 27 September.

The non-linear amplifier gain problem was still apparent and proved to be a strong function of depth (temperature) because shallow water drops remained quite stable. Repeatable attenuation data were collected during three drops to depths of 200, 300, and 600 meters. Of the remaining three drops, two were of the non-linear deep variety and the third failed due to a minor malfunction in the electronics. The background section was plagued with noise and drift problems. Perhaps half of the background data was lost due to either the signal drifting or the excessive noise which developed late in drops B4, B5, and B6.

Prior to the next cruise in November 1968, the electronics of the signal processing circuitry were completely rebuilt. The intent was to fabricate ultra stable circuitry that was

insensitive to varying ambient parameters such as temperature
and power voltages. Laboratory tests indicated that we had
succeeded but the final trial remained at sea.

DOOM Cruise C departed Port Everglades, Florida on
26 November 1968, again with NAD Crane personnel aboard, for
13 scheduled days at sea. Cruise plans included stations
in the Straits of Florida, the Northwest and Northeast Providence
channels of the Bahamas, and two locations in the open sea due
east of the islands. Drop C1 was attempted on the night of
departure in shallow water just off the Florida coast in
fairly heavy seas. In retrospect sea conditions were probably
too rough in that the package was banged severely against the
ship both during launch and recovery which resulted in
misalignment of the α section optics and a shift of the
background zero level off scale. Although calmer seas
prevailed for five subsequent drops, the DOOM system was not
without misfortune. On the next drop when signal traces
became quite noisy and amplifier gains non-linear, the new
circuitry was immediately suspected. Post drop tests revealed
that some minor adjustments were required but no gross malfunction
was discovered which would account for such extreme behavior.
When in-situ troubles persisted, attention was directed to
the possibility of salt water leaks in the external cable
assembly. Visual inspection for moisture on the face of connector
inserts was inconclusive since, O-ring grooves trap water
during immersion which may flow to the insert when plug and
receptacle are disconnected. Connectors were cleaned, dried,
and fitted with new O-ring seals, but the problems continued.
Finally, the resistance from conductor to conductor within the
cable decreased to measurable values, thus proving conclusively
that either the cable or the connector was flooding and the
source of our dilemma. Since no replacement cable was then
carried on DOOM trips, operations were terminated.

After such a disasterous performance on Cruise C,
it was felt imperative that all subsystems of DOOM function
flawlessly in forthcoming sea trials in March 1969. The
defective deep sea cable was replaced and a spare ordered
which would be carried on all future tests. In addition
to the normal laboratory preparations and calibrations
prior to a cruise, additional tests in water were conducted
in the 100 foot deep undersea weapons tank at NOL. All
systems, including the completed scattering section, were
performing satisfactorily until flooding occurred in the deep
sea motor causing irreparable damage to that unit. Since a
replacement could not be delivered before the next cruise,
a fixed mirror was substituted producing a scattering measurement
at a constant angle of six degrees.

Cruise D, essentially a repeat of Cruise C, was scheduled
to depart Key West on 24 March 1969, proceed through the
Straits of Florida and the Northwest and Northeast Providence

channels, and enter the open ocean on 28 March 1969 for deep
measurements east of the Bahamas. About nine drops were
planned, four in transit, four in the deep ocean, and one off
the Florida coast the evening prior to entering Port Everglades
on 2 April 1969.

Temporary loss of the DOOM equipment in shipment resulted
in postponement of sailing until the afternoon of 27 April 1969.
The initial drop that evening was aborted due to sudden
mechanical failure of the A-frame. High seas in the
Straits of Florida prevented operations until the calmer
waters of the Northwest Providence Channel were entered
in the early morning of the 29th. During pre-drop check out,
the 40v battery supplying the mercury arc lamp was inadvertently
shorted to ground, completely destroying the wiring to the lamp,
but fortunately doing no harm to the rest of the circuitry.
Consequently, only the attenuation and background sections were
operating during the early morning drop D1. These, however,
performed flawlessly showing no signs of electronic non-linearity
which had plagued them previously. The Mercury lamp circuitry
was rewired this time incorporating appropriate fusing. Three
drops on successive nights of the 29th, 30th, and 31st, two in
the Providence channels and the last in 3840 meter water at
the mouth of the Northeast channel, resulted in good data
from all three measurement sections from surface to bottom.
On the night of 1 April two short drops were made off the coast
of Florida opposite Fort Lauderdale, the first in the middle
of the Gulf Stream, the other as close to shore as safety
permitted. Both were successful.

DOOM Cruise E departed Norfolk, Virginia on 17 October 1969
aboard the USNS LYNCH for two weeks of tests in the Atlantic.
Piggybacking on this trip were a group of graduate students
and faculty from the Oceanography Department at the Florida
State University who were to conduct on a not-to-interfere
basis their own independent program of biological measurements.
The only major equipment modification was the installation of
the new stepper motor permitting scattering measurements from
six degrees to 92 degrees. Seven stations were planned, the first
in shallow water just off the Virginia Capes, the second
further from shore in the Gulf Stream. From there we were
to proceed southeast to a deep water station about 360 nautical
miles east of Cape Fear and then track due south, occupying
several stations in route, to the final operating area east
of the Bahamas.

Although rough seas forced postponement of a drop the
first night out, the weather cleared permitting successive
drops on the following three evenings, the first in coastal
waters and the succeeding two in the Gulf Stream. All sections
performed quite well during drop E1. Drop E2 data was lost
because of failure of the recorder lamp just prior to the package
entering the water. Scattering data, now recorded as a function

of angle, looked good until a depth of about 2100 meters was
reached during drop E3 where the stepping motion apparently
missed a step thus confusing the angular orientation of the
mirror. The torque of the motor proved to be insufficient to
consistently drive the mirror when subjected to the large
hydrostatic pressures of the deep ocean. On all subsequent
drops during the cruise, the motor similarly malfunctioned
when reaching depths of around 2000 meters. The background
section also began having troubles as evidenced by a decrease
in sensitivity and an increase in the noise level.

The next several days, 21 to 27 October, were characterized
by rather high seas, which hindered operations to the extent
that only three drops were completed at as many stations over
the Hatteras abyssal plain. Minor shipboard modifications
failed to correct the background and scattering problems.
A peculiar accident befell the DOOM package during the final
drop E6 on the 27th. At a depth of about 650 meters, it
apparently struck a large object which momentarily inverted
it, causing the lifting bridle wires to snarl on an appendage
of the framework, thus tilting the package on its side for the
remainder of the drop. The inversion also caused the
misalignment of an α section component and the consequent loss
of data for the rest of the drop. Cruise E was terminated on
31 October at Port Everglades.

Since the next DOOM cruise was scheduled to embark from
Port Everglades in early January, DOOM material was offloaded
at the NOL Test Facility, Fort Lauderdale where pre-cruise
maintenance and calibration were performed. Modification made
at this time were (1) the replacement of the background section
photomultiplier which appeared to solve our problems there and
(2) increases in voltage and capacitance of the stepper drive
circuitry in order to increase torque of the motor.

The primary operational area for DOOM Cruise F of
January 1970 was the Brownson Deep located toward the western
end of the deep trench just north of Puerto Rico. Four to
Five measurement drops were planned at stations along the route
during a one week transit to the trench area, via the Florida
Straits and the channels north of Cuba and Hispanola. An
additional five to six drops were anticipated in the
Brownson Deep. Just prior to sailing on 6 January, NAVOCEANO
operations requested that we not transit via our planned
route due to delicate international relations prevailing in this
area, but rather proceed through and swing east of the Bahamas,
and enter the trough area through a passage east of Cuba. A
further loss of one day was incurred when the ship was
detoured to the port of Nassau to discharge a seasick technician.

A record high of ten DOOM drops were made on successive
nights from 10 January 1970 through 19 January 1970 at five

different stations beginning in the sheltered sound south of
Long Island in the Bahamas and terminating with five drops in
the Brownson Deep. Three stations north of Hispaniola were
sampled in route. A most unfortunate accident had occurred
when the DOOM system was assembled for sea in Fort Lauderdale.
As the end cap of the optics cylinder was replaced, several
power wires carrying 28 VDC and 115 VAC were pinched and
consequently shorted, resulting in seemingly catastrophic
failure when DOOM was first run at sea. Although damage
was repairable since fusing had protected the circuitry,
some degradation of performance of certain components was
evident. The background section was one of these casualties,
producing virtually no usable data during the tests. Performance
of the control circuit of the stepper motor was affected to
the extent that on five drops a scattering measurement at only a
constant six degree angle was attempted. The α section
functioned properly.

Only seven of the ten drops yielded usable data however
due to a variety of component failures. External electrical
cables flooded in one case, the recorder magazine failed
to feed properly in another, and a DC power failure aborted
the third. Of the seven successful measurements four were
made in the deep trench and three in route. The stepper
motor again failed to function properly when at depths in
excess of 2000 meters.

In addition to normal surface to bottom studies, a
plankton concentration - optical transmission correlation
experiment was attempted on two drops. The Florida State
University contingent deployed ten plankton nets, spaced
every 20 meters, to a depth of 200 meters over a time interval
of about 1.5 hours. DOOM was simultaneously lowered, taking
care to pause for several minutes at the depths of the deployed
nets. This test was performed late in the evening so that
vertical migrations of the plankton with decreasing ambient
light would be stabilized.

Chapter 7

SAMPLE DATA

The DOOM program has produced moderate quantities of pertinent optical oceanographic data on transmission, scattering, and backgrounds in the ocean during five of the mix measurement cruises.

Types and amounts of reliable data obtained are summarized as follows:

(1) Spectral attenuation - surface waters during Cruise B, surface to bottom for Cruises D, E, and F.

(2) Scattering - $\sigma(\theta)$ at six degrees during Cruise D and part of Cruise F; $\sigma(\theta)$ from six to 90 degrees to depths of about 2000 meters for Cruise E and part of F.

(3) Background - Moderate success on Cruises A, B, and D. Illustrative examples of the above types of data which have been reduced, are now presented with comment on relevant features and some comparison to laboratory measurements.

Spectral attenuation coefficients at two wavelengths, 408 mμ in the violet and 482 mμ in the transmission window are plotted along with temperature as a function of depth in Figure 17. This data, taken in October at a station slightly north of the Gulf Stream some 450 nautical miles off the New Jersey coast, illustrates a typical attenuation profile for surface waters. Attenuation, which is fairly constant in the isothermal surface water to about 50 meters, changes quite dramatically at the thermocline, the coefficients increasing rapidly by about 40 percent before falling continuously with depth. This attenuation peak is attributed to plankton and detritus which tend to concentrate in layers above strong temperature gradients.

A deep water profile of attenuation and temperature is shown in Figure 18. This data was recorded at a station located in 3840 meter water in the Atlantic at the mouth of the Northeast Providence channel in April. After a slight peak, which again occurs at the top of the thermocline, the attenuation at 500 mμ drops to a minimum at about 500 meters and remains fairly constant at $0.045 \pm .005$ m^{-1} all the way to the bottom.
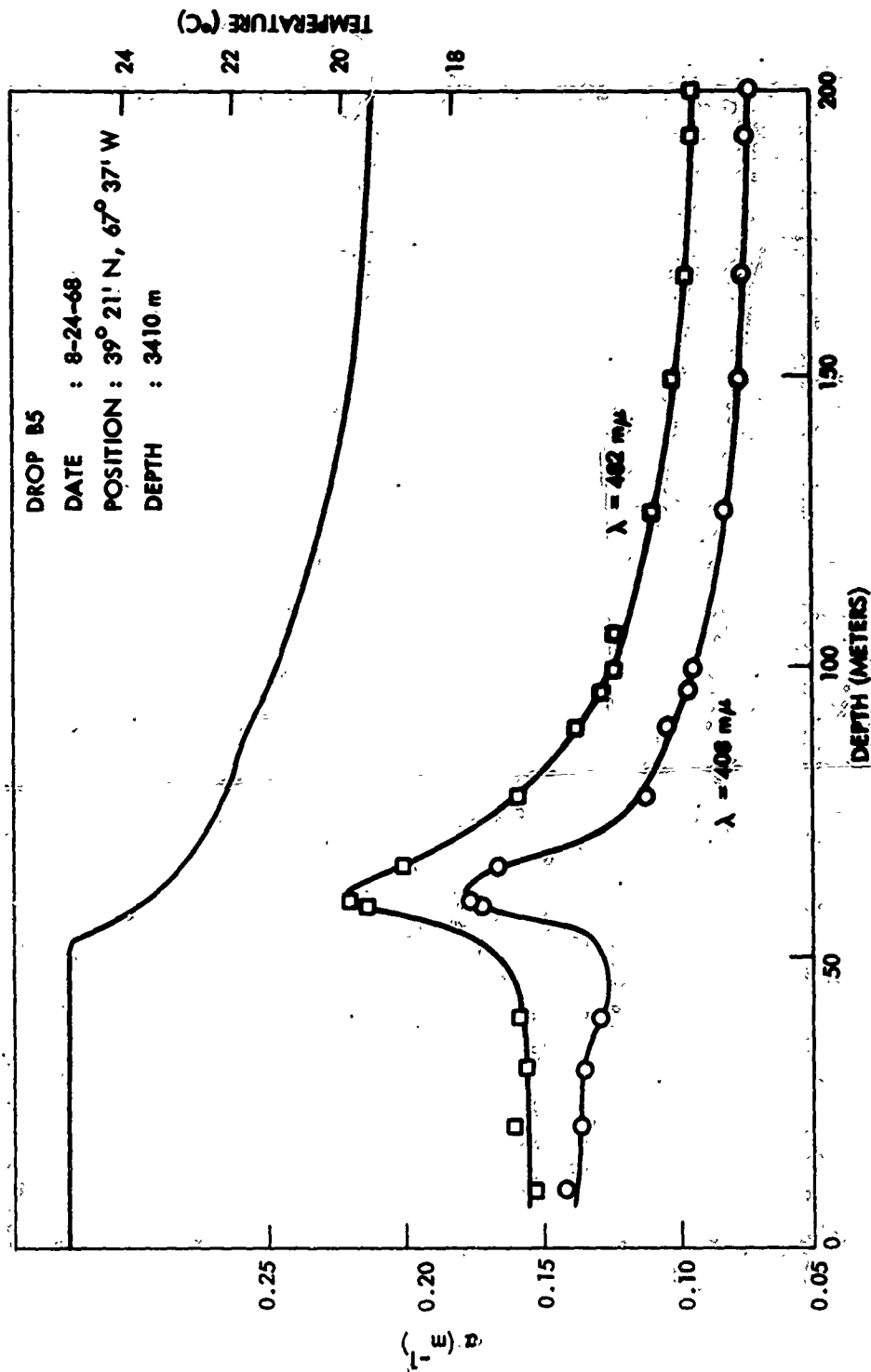
FIG.17 OPTICAL ATTENUATION AND TEMPERATURE PROFILES OF SURFACE WATERS IN THE NORTH ATLANTIC
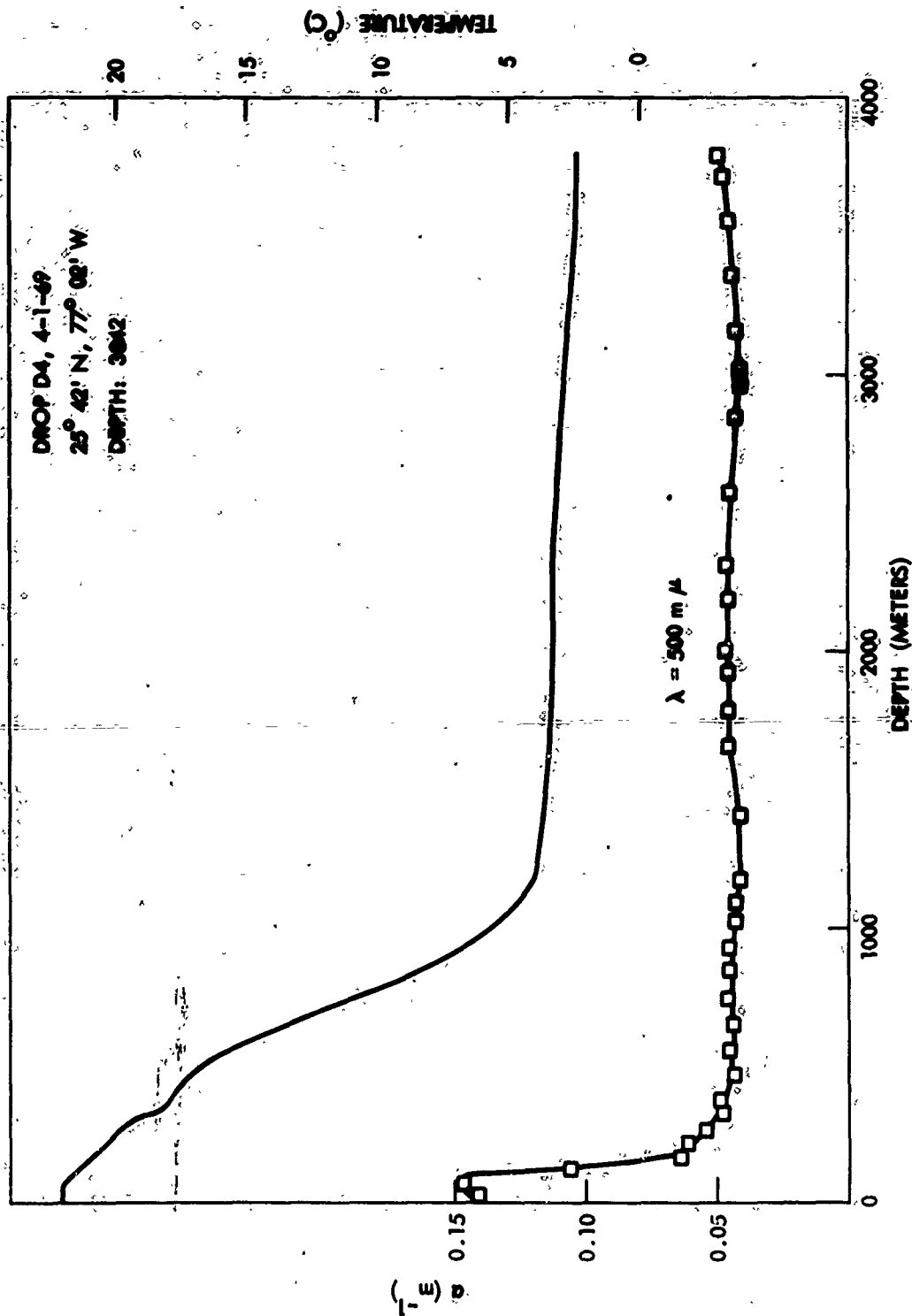
FIG. 18 OPTICAL ATTENUATION AND TEMPERATURE PROFILE EAST OF THE BAHAMAS

It is quite evident that the higher turbidity in the surface
waters of the photic zone are the result of the concentration
of living organisms here, primarily the phyto and zoo-plankton
and their waste products.

A number of interesting features may be observed in the
α and temperature profiles of Figure 19 which were measured
during drop E3 in the Gulf Stream off the Virginia Capes in
October. Several temperature inversions were present in the
stratified surface layers of the upper 150 meters shown here
with an expanded depth scale. The correlation between optical
clarity and temperature gradients is quite apparent. In
fact on the slopes of the strongest inversion centered at
about 80 meters, the transmission was so weak that the α signal
went off the low end of the scale of the recorder. Below the
stream waters, the more or less regular temperature decrease
with depth was accompanied by a similar slow decrease in α
reaching a minimum of 0.048 m^{-1} at about 2500 meters. At a
depth of 2800 meters or about 345 meters off the bottom, the
attenuation begins to increase and continually rises to
0.066 m^{-1} at 3065 meters when the package was stopped some
80 meters from the bottom. This increase in turbidity near the
bottom is common in areas where deep currents stir up loose
sediments and silt from the bottom.

Let us now consider the variation of attenuation as a
function of wavelength. Spectra from the previously discussed
Gulf Stream drop E3 are plotted at selected depths in Figure 20.
Aside from the higher attenuation of the surface waters, two
features of the spectra are worthy of note. There is a basic
difference in the relative shape of the attenuation spectra
for surface and deep water cases. For surface waters the
attenuation in the blue-violet wavelength interval clearly
exceeds that of   longer wavelength in the yellow-green interval.
The converse is true in the deep water where the coefficients
at the shortest wavelength 386 m_μ are slightly below those of
the longest 555 m_μ. This change in shape results in the second
feature of note, the shift in location of the spectral
transmission maxima. In clear waters, it falls near 480 m_μ
but shifts to the longer wavelengths, 490 to 500 m_μ, in the
more optically dense surface waters.

The most turbid waters of the ocean are found in the
shallow coastal areas of the large continental land masses;
those measured by DOOM were located about 35 nautical miles
off the Virginia Capes during drop E1. Except for the magnitude
of the attenuation which is considerably higher, the spectral
curves, Figure 21, show a simularity in shape to the previous
surface water measurement of the Gulf Stream. Transmission
maxima are shifted to the longer wavelength, about 500 m_μ,
and the short wavelength attenuation far exceeds that of the
longer wavelengths. Values of coefficients at the extreme
short wavelengths are not shown because signal levels, due to

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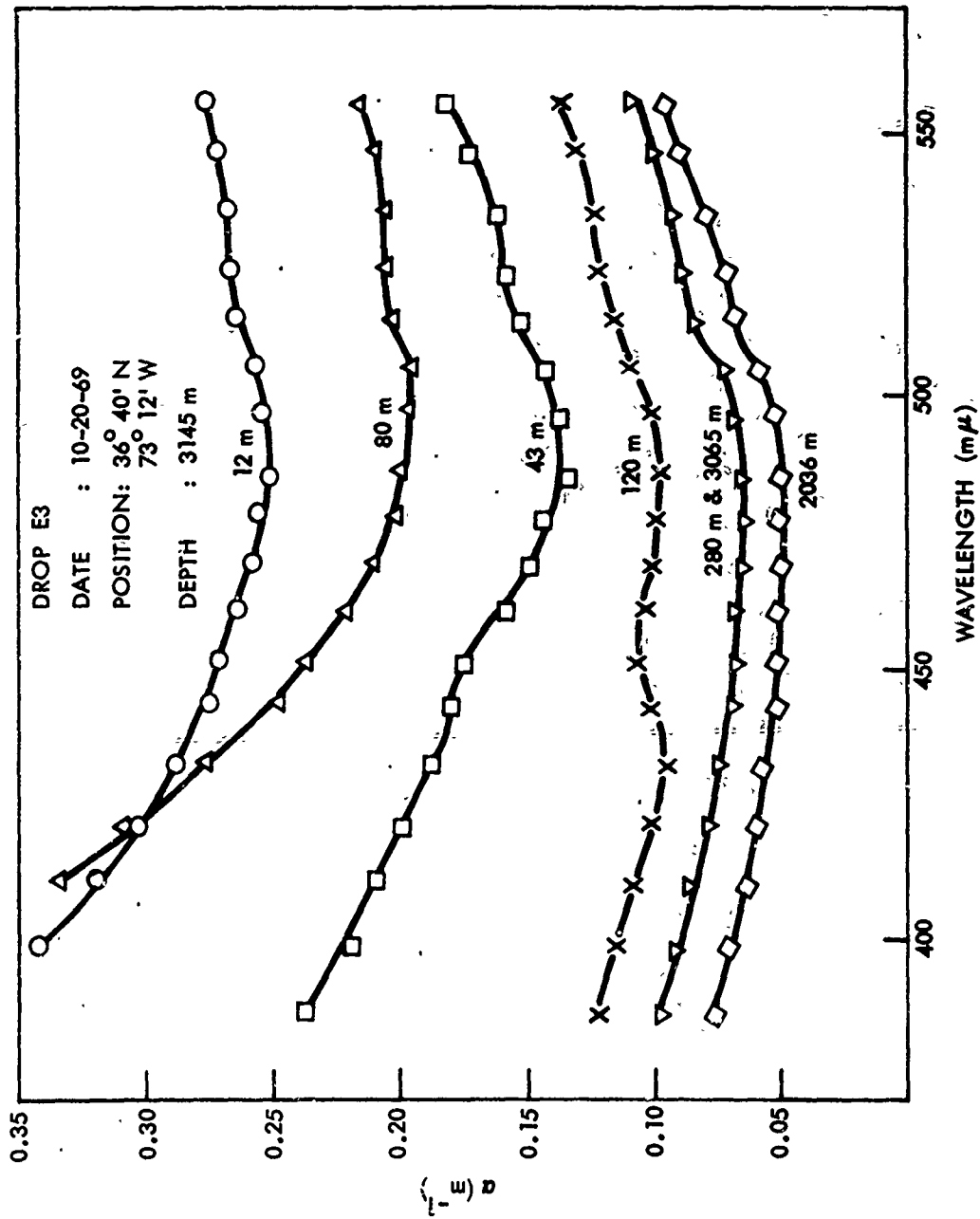
FIG. 20 OPTICAL ATTENUATION SPECTRA AT SELECTED DEPTHS IN THE GULF STREAM OFF
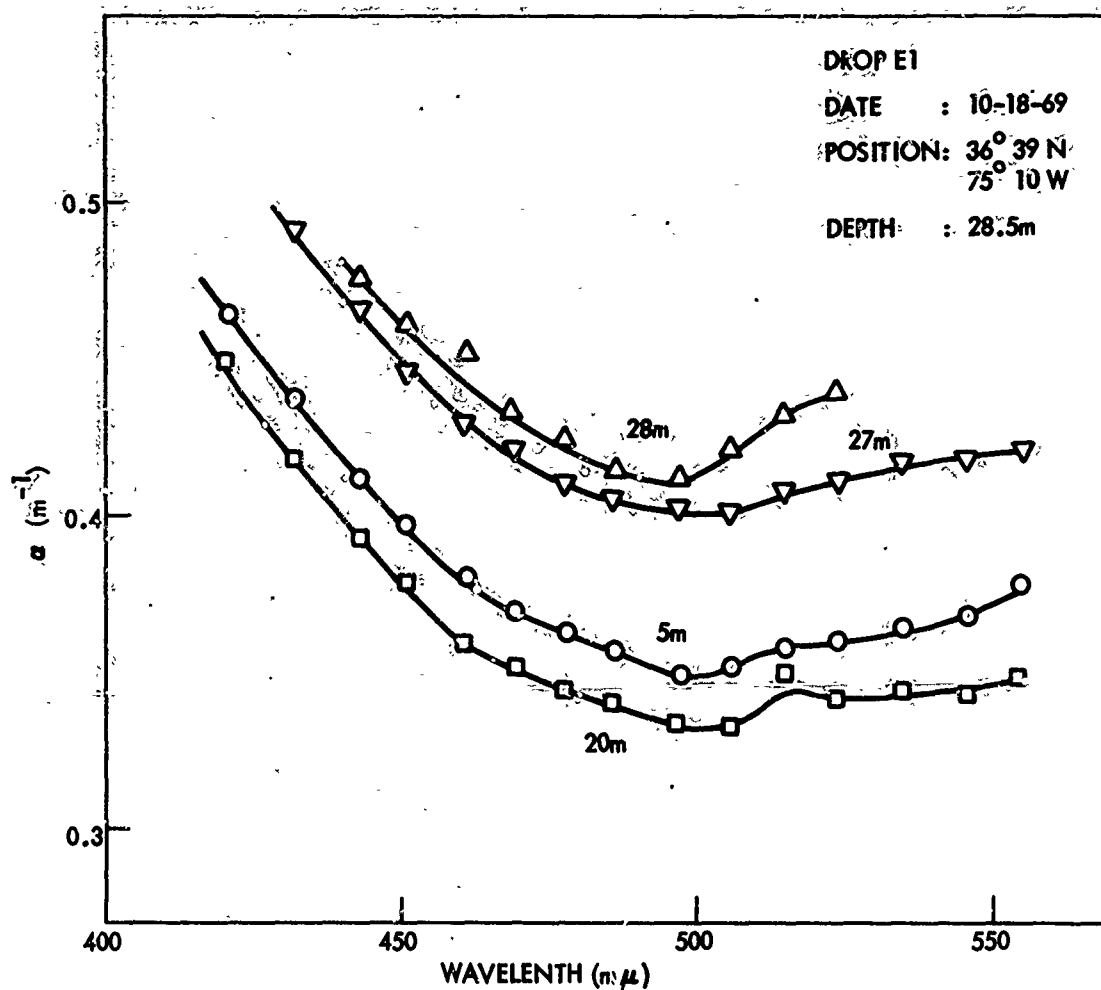THE VIRGINIA CAPES

FIG. 21 OPTICAL ATTENUATION SPECTRA AT SELECTED DEPTHS IN COASTAL WATERS

high turbidity, were so low that they fell off the low
end of the recorder scale.

In contrast to the coastal and surface waters, the
intermediate layers extending to great depths in the oceans,
are remarkably optically clean, surpassing in some spectral
regions even the purest produced in the laboratory. In
Figure 22 are contrasted spectra of deep in-situ measurements
of drop E5 over the Hatteras Abyssal plain east of Cape Kennedy,
Florida with those of pure water produced in the laboratory
by three separate investigators. The in-situ spectrum at 2040 m,
typical of the clear water column for this drop, falls below
those measured in the laboratory at wavelengths shorter than
the window region at 480 m_μ, indicating a clearer, more
transparent medium from the ultraviolet through the blue than
has been produced or at least measured in the laboratory.
The only close measurement is that of Sullivan, of recent
origin, and perhaps this points out the extreme difficulty of
artificially producing scatter-free water. The trend of deep
ocean waters to be relatively cleaner at the shorter wavelengths
can also be seen in the spectrum recorded 300 meters from the
bottom at 4660 meters. Although attenuation coefficients are
from 0.03 to 0.04 m^{-1} higher than the clearer in-situ water,
the spectral shape remains roughly the same and at the short
wavelengths, below 400 m_μ, is below the laboratory measurements
of Hulbert and Matlack.

Scattering data may be presented in a manner similar to
the attenuation profile, as in Figure 23, where the volume
scattering function at an angle of six degrees is plotted as a
function of depth. Also included is a plot of α at 432 m_μ near
the wavelength (436 m_μ) of the scattering measurement which is
used in the calculation of $\sigma(\theta)$. This data was taken during
drop D3 in March in the Northwest Providence channel. An
expanded depth scale is used in the first 400 meters. Since
scattering is one of the mechanisms contributing to the
attenuation process, one might expect the scattering function
to vary in a manner similar to the attenuation. And indeed it
does at most depths; the maxima, minima, and slopes of the
two curves nominally following one another. The exception
occurs between 400 and 600 meters where α begins to slowly
increase while $\sigma(6^\circ)$ continues to decrease before starting a
slight rise at 650 meters. It must be concluded then that this
increase in α is due to absorption by dissolved impurities
rather than by an increase in scattering from particulate matter.

Scattering data may also be presented as a function of
scattering angle as in Figure 24 where the volume scattering
function at 436 m_μ is presented for an in-situ measurement
from drop E1 in coastal waters off the Virginia Capes. For
comparison laboratory measurements of regular and filtered
tap water are also included. The angular range of the in-situ
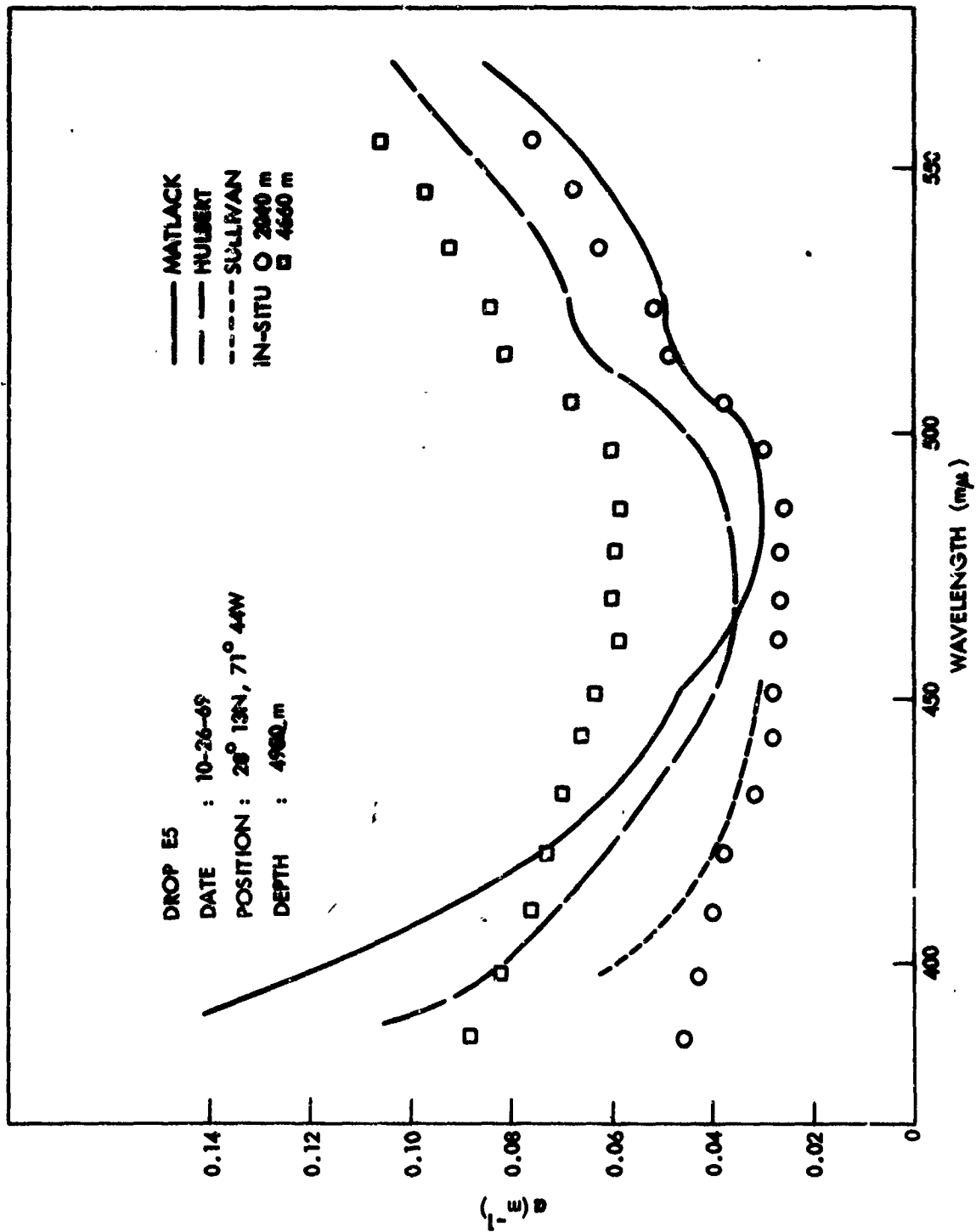function extends only from six degrees to 48° because extremely low

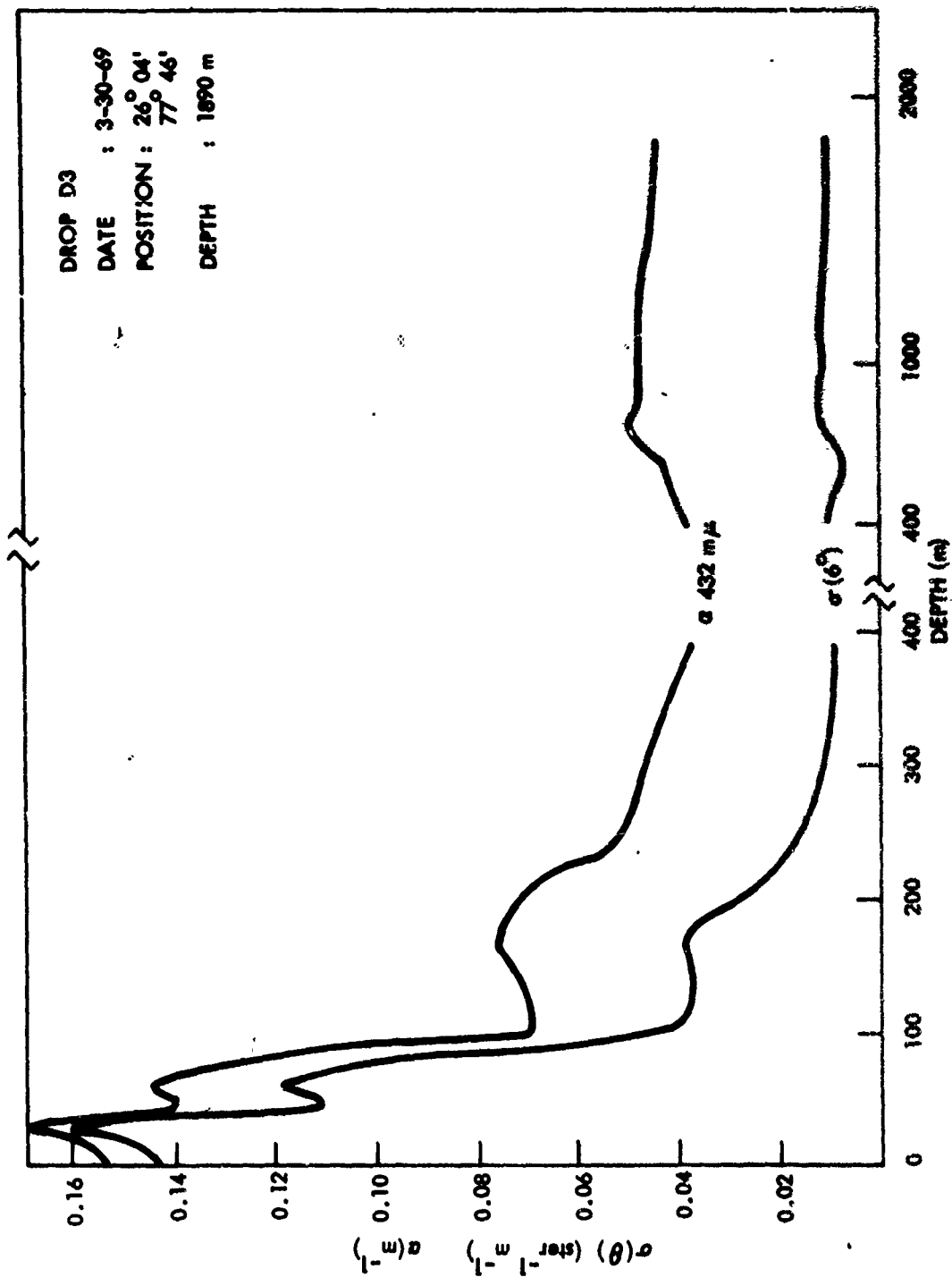FIG. 22 COMPARISON OF SPECTRAL ATTENUATION COEFFICIENTS OF PURE AND NATURAL WATERS

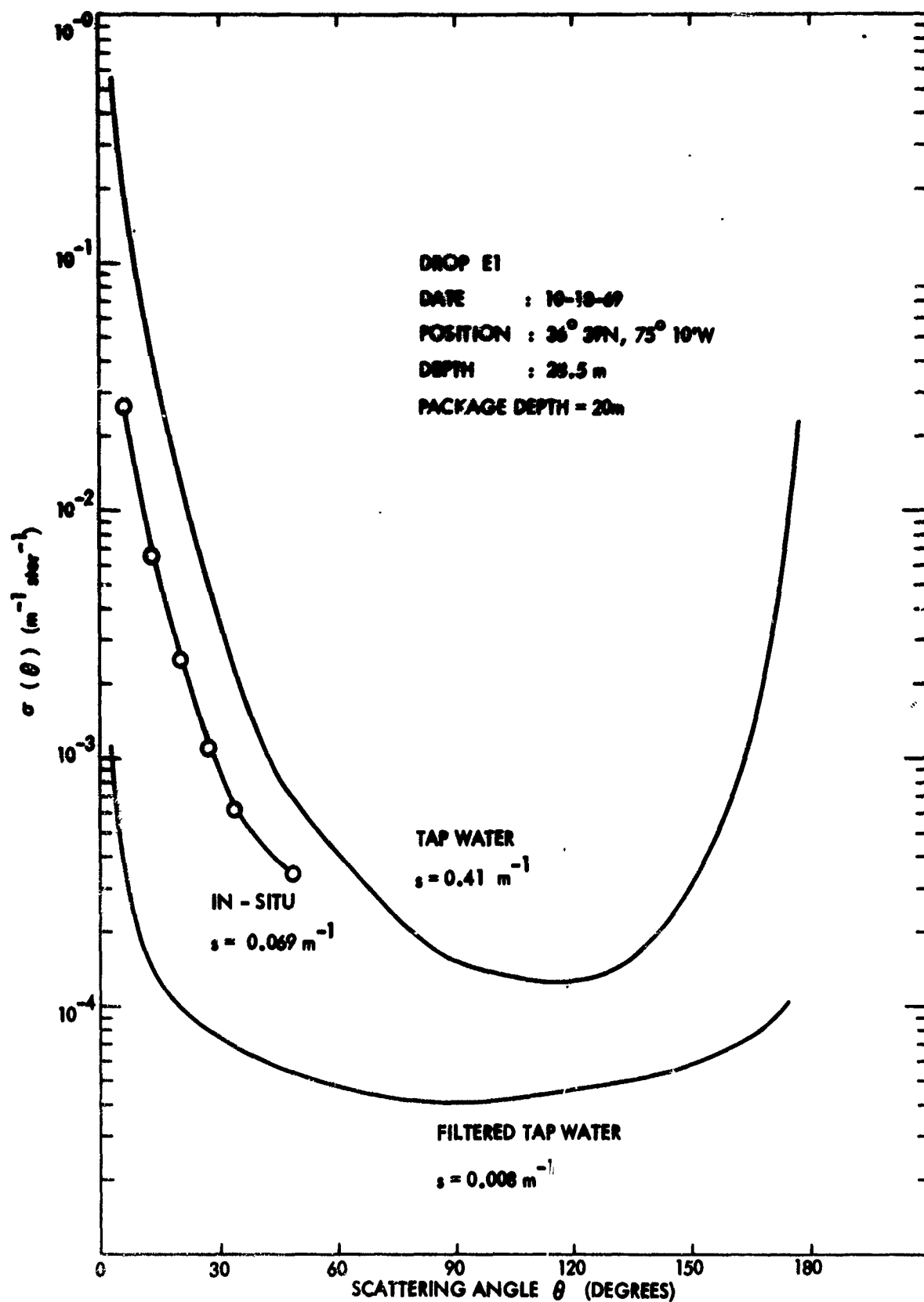FIG. 23 OPTICAL ATTENUATION AND SCATTERING PROFILES IN THE NORTHWEST PROVIDENCE
CHANNEL

FIG.24 COMPARISON OF IN-SITU AND LABORATORY MEASUREMENTS OF THE VOLUME
SCATTERING FUNCTION AT 436 mμ

signal levels at larger angles fall below the linear range
of the logarithmic amplifier. This rather turbid coastal
water produces a curve which falls between regular and filtered
laboratory samples, indicating perhaps very strong particulate'
scattering in city water supply. To obtain the total volume
scattering coefficients the function must be integrated from
zero to 180 degrees; but our measurement is from only six to
48 degrees. If we examine the function for tap and other
natural water measurements, we find that the smaller angles
below 48 degrees contribute over 90 percent of the total area
beneath the curves. Applying a ten percent correction to the
in-situ integration, an s of 0.069 m^{-1} is obtained. This
constitutes about one-sixth of the attenuation coefficients
which was measured at 0.41 m^{-1} and would lead to the conclusion
that attenuation was due primarily to absorption by yellow
substance or other dissolved impurities.

The background measurement is a passive qualitative
reception of sporadic signals and, therefore, does not lend
itself to concise analytical presentation. Rather, the data
must be evaluated on a statistical basis and correlated with
the other optical and physical parameters which are recorded.
A sample of raw data showing a high incidence of luminescent
flashing is presented in Figure 25. These traces were recorded
during drop B5 in the Atlantic north of Gulf Stream about
450 nautical miles east of New Jersey. They are slightly
over one minute in length in order to include the complete
background data recording interval with two shutter closures and
a complete α spectrum which at this time was scanned at a one
per minute rate. Real time is determined from the two-second
markers, starting from the left at the α spectrum turn-around
at 1924:00. During the time interval of this record, the
package was lowered a distance of about six meters, from a depth
of 60 to 66 meters. A strong irregular temperature gradient
is observed on the bottom temperature trace beginning around 1924:38.

Even though the measurement was made after dark, a sizable
ambient background signal is present at this depth above the
dark current level observed during the shuttered period. The
rate of recorded flashings appears to increase somewhat from
less than one to perhaps several spikes per second when the
gradient is entered. Frequency of flashing is presumably
proportional to the number of luminescent organisms within the
field of view while the magnitude of the flashes will vary due
to a number of factors, i.e., proximity, radiance, size, and
position within the field of view. In this region of high
luminescent activity, attenuation is severe and spectral
signals fluctuate rather rapidly as can be seen from times
1924:45 to 1925:00. To illustrate the rippling effect that
luminescent plankton have on the attenuation measurement, a
second record taken nine minutes later at a depth of 100 meters
is presented. Figure 26. Only occasional spiking is observed
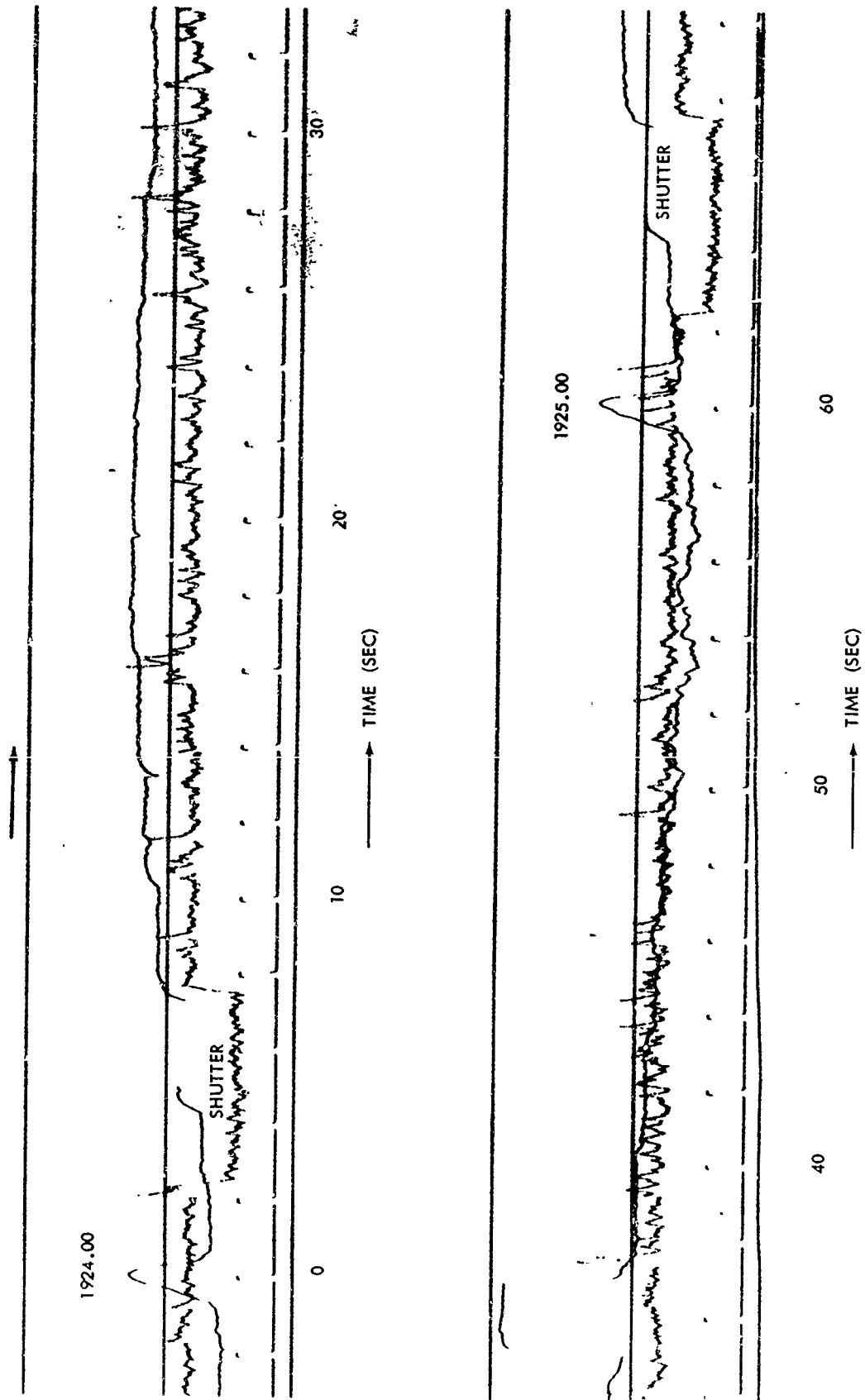and the ambient illumination is at the dark current level.

FIG. 25 BACKGROUND DATA IN A TEMPERATURE GRADIENT SHOWING A HIGH INCIDENCE OF LUMINESCENT FLASHING
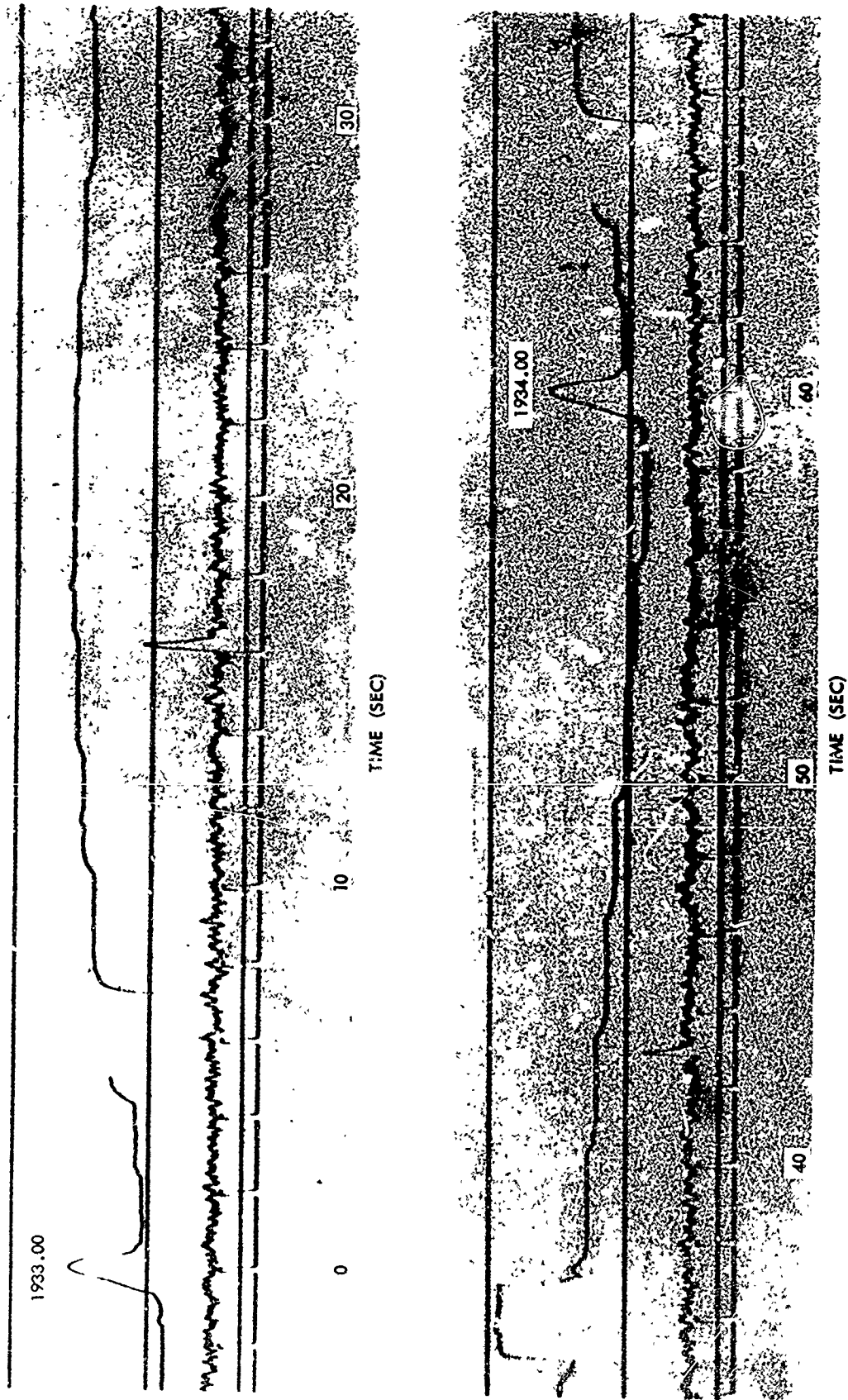
FIG.26   BACKGROUND DATA FROM ISOTHERMAL WATER SHOWING A LOW INCIDENCE OF
LUMINESCENT FLASHING

It is seen that the α signal is higher and much smoother. The coefficient at 482 mμ has a value of 0.095 m^{-1} as compared to 0.170 m^{-1} at 60 meters. A correlation is indeed established between attenuation and the population of luminescent plankton.

Chapter 8

FUTURE PLANS

This report has described and summarized the DOOM effort
to date with emphasis on equipment and the data gathering
processes rather than on data presentation and analysis. The
reasons for this emphasis are two-fold:

(1) The DOOM effort has been concentrated on developing
a seaworthy system that will reliably produce the quality of
optical data which we desire and then on operating that system
in the field so as to amass a representative sampling of
transmission phenomena of ocean waters.

(2) Much of the raw data has not been processed due
to manpower limitations and thus the quantity of data reduced to
date is not sufficient for rigorous analysis and interpretation.
Data reports with appropriate analysis, will follow as the
processed results become available.

Field measurements will continue in FY 1971 and FY 1972
with three proposed cruises which should complete the survey
of Atlantic Ocean waters. The first cruise will sample
Carribean waters in the vicinity of the Bartlett Deep in
February and the second will investigate the plankton-rich
waters south of Nova Scotia and Laborador in May-June 1971.
Still in the planning stage is a final measurement cruise to
the Mediterranean in March or April 1972. Although no
commitments have been made past FY 1972, interest exists in
exploring other ocean areas, namely the Arctic beneath the ice
caps and possibly some regions of the Pacific or South Atlantic.

No major modifications to the DOOM system nor in measurement
techniques are anticipated in future studies. However,
additional physical and biological sampling of ocean parameters
concurrent with DOOM operations may be desirable. Such data
might include salinity and dissolved gas determinations, or
chemical analysis of organic absorbing elements.

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DOCUMENT CONTROL DATA - R&D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY (Corporate author)	2a. REPORT SECURITY CLASSIFICATION
Naval Ordnance Laboratory	UNCLASSIFIED
White Oak, Silver Spring, Maryland 20910	2b. GROUP

3. REPORT TITLE

The Deep Ocean Optical Measurement (DOOM) Program

4. DESCRIPTIVE NOTES *(Type of report and inclusive dates)*
Summary (July 1967 – January 1970)

5. AUTHOR(S) *(Last name, first name, initial)*

Donald E. Matlack

6. REPORT DATE	7a. TOTAL NO. OF PAGES	7b. NO OF REFS
18 January 1971	71	24

8a. CONTRACT OR GRANT NO.	9a. ORIGINATOR'S REPORT NUMBER(S)
b. PROJECT NO. TASK ORD-03C-000/092-1/R104-03-01	NOLTR 70-165
c.	9b. OTHER REPORT NO(S) *(Any other numbers that may be assigned this report)*
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13. ABSTRACT

A shipborne system is described and results of in-situ measurements of the inherent optical properties of ocean water are presented. This Deep Ocean Optical Measurement (DOOM) system is designed to measure to any depth in the ocean spectral attenuation coefficients from 380 to 560 millimicrons, the volume scattering function at 436 millimicrons through an angular range from six to 92 degrees, and background illumination of both celestial and biological origin. Representative data obtained from December 1967 through January 1970 on six measurement cruises to various areas of the Atlantic are presented. Future cruises and plans are discussed.

DD FORM 1473
1 JAN 64

14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Spectral attenuation measurement of ocean water Light scattering measurements of ocean water In-situ optical measurements Deep ocean optical measurements Underwater light transmission optical oceanography						

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